Effect of Physical and Mental Workload Interactions on Human Attentional Resources and Performance

A thesis submitted for the degree of Doctoral of Philosophy

By

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‘O lord! Increase me in knowledge.’

[*Surah Taha: Ayah 114*]

Author's Declaration

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Abstract

Many tasks in the real world require simultaneous processing of mental information alongside physical activity. Most of researchers have studied the impact of physical activities on simple cognitive tasks, but have neglected other important influences (such as different attentional resource pools, as well as gender). Therefore, this thesis proposes a new model that investigates the combined impact of physical and mental workload on different attentional resources (visual and auditory, verbal and spatial).

This thesis presents three experimental studies that examined the effects of physical and mental workload interactions, as well as gender, on visual tasks performance and auditory tasks. This thesis uses different methods to evaluate the impacts of workload interactions on task performance: performance measure, physiological parameters and brain activity (Near-Infrared Spectroscopy (NIRS) method) and subjective assessment tools. Finally, this thesis translates the experimental studies setting into a field study to validate the model.

Based on the experimental results, this research creates a new theoretical model that illustrates in general that physical activity is beneficial for performance on cognitive tasks (visual and auditory), particularly at low levels of workload interactions, while other workload interactions lead to worse performance on cognitive tasks. However, when physical activity was introduced, performance at the medium level of mental workload was equivalent to that in the low mental workload condition; furthermore, at the low mental workload, there were no differences in performance between low and medium physical workloads. The general pattern of results suggests that physical workload leads to better performance in these medium-demand conditions up to the higher level in the low-demand condition. A mechanism for this effect is proposed based on physiological arousal and brain oxygenation. This thesis further suggests that the NIRS is a valuable technique to reflect the influence of physical and mental workload interactions on brain activity. Finally, this thesis demonstrates the translation of experimental findings into a field setting to verify the new model as well as to make recommendations for job design.

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Publications

1- Basahel, AM., and Young, MS., 2009. Effects of the Interaction between Physical and Mental Workloads on Worker Performance, In: *Proceedings of the 2nd SED Research Conference 2009,* Brunel University, London, June 22-24, pp.59-61.

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CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

This chapter provides an introduction to this thesis, including the rationale for studying work system design in dual-task environments by balancing the physical and mental workload of occupations that include both physical and mental workloads (e.g. fire-fighting and assembly jobs). This research was carried out with the aim of investigating the impact of physical and mental workload on attentional resource capacity. To achieve this aim, the work involved the development of a sequence of three experimental studies to produce results that led to a new model, which explains the interaction of physical and mental workload with attentional resources. A field study was also conducted to validate the model which led to recommendations for industrial situations such as product assembly. This chapter states the importance of balance between job workload requirements and individual attentional resources. The objectives of the research are outlined and the structure of the thesis is presented.

1.2 BACKGROUND

At present, the evaluation of (concurrent) physical and mental workload (see Appendix A) is a major issue in the research and development of the human-machine interface in search of higher levels of productivity, comfort, and reduction of injuries in the workplace. A balancing act between task workload and attentional resource capacities is a key point in terms of operator performance and efficiency, in particular, in the real-world domain of a multitasking environment. In this research, the term "multitasking environment" refers to the mental and physical task workload which a worker performs concurrently. This issue is left to the designer, who usually aims to increase the level of comfortable in work-system by adding technologies such as automatic conveyors and robotics. This contrasts with the ergonomics philosophy of matching those systems to attentional resources limitations, so the result of increasing technology is not a positive thing in all types of jobs. The ergonomics researcher's aim is, instead, to regulate work system demand to the individual's attentional resource capacities so they are neither low workload nor overloaded. There is also the danger of too heavy a mental load not being recognised in the same way as physical overload, especially with automation of work systems. Therefore, ergonomics researchers focus on this issue in order to ensure safety, comfort, and long-term efficiency, since some jobs still require physical action in addition to mental effort (such as positions in the military, firefighting, and industrial sectors). For example, operators who work on assembly production lines require both physical and mental activity to perform assembly tasks. In particular, those who perform highly physical work, in addition to visual attention or auditory resources, may find that performance will suffer. That may occur because the designers of these types of tasks often do not consider the balance between physical and mental workload against the operator's attentional resource capacity. This lack will lead to poor system design. As a result of disregarding the need to balance these issues in work system design, the various amounts of physical effort interact with mental loads and could place stress on operator performance, which leads to increased errors, lost time, and injuries. Additionally, an increase in workload caused by other factors apart from physical stresses (e.g., noise and temperature) leads to increased arousal stress on the operator; this, in turn, leads to deterioration in performance.

Measuring workload is critical to designing operating systems (Tsang, 2001). The literature review in Chapter 2 highlights the limitations of previous research into the impact of physical and mental demands on performance. Thus, the data from the current thesis are required to fill the gap in ergonomics literature around its approach to physical and mental workload versus performance. Moreover, such data are needed by designers to harmonise and optimise operator performance and balance task demands and operator capabilities.

In assessing workload, it is important for the designers of operating systems to consider appropriate data on human mental capabilities (Hollnagel, 1999). This thesis concludes by establishing a new theoretical model which explains the correlation between different levels of physical and mental workload against the attentional resources model by Wickens (1984). In addition, it provides valuable guidance to designers who develop and create work systems in product assembly factories, as to how they can consider appropriate workload interactions of the system as a key factor in operator performance.

1.3 DEFINITION OF THE PROBLEM

Physical exercise has been shown to have a positive impact on cognition. A medium level of physical exercise leads to better performance by increasing the level of arousal (Audiffren et al., 2008). However, the researchers who have studied the influence of these effects on performance reported different findings. Some of them found that the physical and mental loads did not impact on human responses (e.g., Lemmink and Visscher 2005; Perry et al. 2008), while others found that intermediate and high levels of physical workload impeded performance (DiDomenico and Nussbaum, 2008, 2011). However, most researchers have concluded that intermediate levels of physical loads facilitate mental tasks and information processing (e.g., Brisswalter et al., 2002; Joyce et al., 2009; Reilly and Smith, 1986). Furthermore, most studies have investigated the influence of mental and physical demands on individual performance separately (DiDomenico and Nussbaum, 2008). Furthermore, variable findings regarding the influence of physical activity on cognitive performance have been reported. Physical workload can impact on attentional resources through physiological arousal levels. Therefore, an increasing level of arousal induced by high physical activity could lead to poor mental task performance. On the other hand, a moderate level of physical load could support mental responses.

Issues of attention and performance have been studied in depth. Numerous authors have examined human information and response processes during dual-task demands. Wickens (1984) proposed the multiple attentional resources model instead of single resource theories; in this model, he addressed the idea that each individual has different and separate resources and these resources have different capacities. Furthermore, Wickens (2008) mentioned that this model depends on two main input senses: visual and auditory. In turn, these resources are characterised by separate capacity limits depending on the type of mental demands, i.e., verbal or spatial. In this model, Wickens' (1984) aim was to explain how operators can perform two separate mental tasks at the same time (time-sharing). The model implies that, in the dual-task paradigm of mental tasks, if the workload of one task or both exceeds the upper capacity limit of attentional resources, then performance will decline. In respect of this model, most researchers have focused on the evaluation of mental workload effects on attentional resource capacities in single- and dual-task environments (Wickens, 2008). In previous studies, there has been a lack of investigation of the impact of physical workload on these resources. Consequently, it is necessary to examine the combined influence of physical and mental workload on these attentional resources in order to identify the role of physical load in the model.

The interactions of low mental workload and physical workload need to be considered. According to Young and Stanton (2002[a]), low mental demand may cause performance to suffer through low physiological arousal levels, which in turn decrease attentional capacity. Therefore, the authors proposed that a reduction in attentional capacity occurs due to a lack of cognitive activity and low arousal. Meanwhile, some studies have reported that moderate levels of physical activity facilitate information processing in some mental tasks through an increase in arousal levels (Audiffren et al., 2009). Therefore, it is worthwhile to examine the interactions between different levels of physical workloads and low mental load to determine if there are any improvements in performance through increasing arousal levels by physical activity.

In fact, the effect of multi-task workload (physical and mental demands) on attentional resource capacity in the real world is not considered a critical point in work-systems design. Designers focus on improved technology in these systems. This is not a favourable approach from an ergonomics perspective since it may lead to increased mental demands as well as physical demands. In addition, the operators who work on these types of tasks generally use at least one perceptual input (visual or auditory) in addition to performing their physical actions. In particular, many jobs require physical activity in addition to mental tasks since, even with increasing automation in most jobs; there are still some jobs that involve physical loads, such as in the industrial and military sectors. For example, in product assembly tasks, operators need to assemble sub-parts to complete the main product. Thus, the operators need to use their cognitive functions such as perception, visual, monitoring and, sometimes auditory resources as signals. In addition, physical activities are required, such as carrying parts, tools, joining the parts, and so forth. In some cases, the operators perform different levels of physical workload, especially in heavy assembly products and traditional assembly factories (i.e., the assembly task depends on manual work rather than automation).

In addition, according to Yagi et al. (1999), one of the most serious limitations to studies that investigate the impact of physical and mental demands on performance of research is that most researchers neglect the impact of gender differences in performing physical and mental tasks concurrently. The current research will help bridge this gap in ergonomics literature and help to generalise the data and to present the gender differences from physiological perspective.

Thus, it is necessary to develop a new theoretical model to explain the mechanism of interaction between physical and mental workloads against the different attentional resource pools (visual and auditory; verbal and spatial). In addition, it will be necessary to validate this model in the field (e.g., a product assembly task). This thesis aims to develop such a model and test it in the field.

1.3.1 Novel Physiological Measures of Physical and Mental Workload

Recently, some researchers have suggested that brain activity measures indicate the stress of workload on information processing, since they reflect the balance between oxygen consumed to perform the tasks and the actual amount of oxygen delivered (Perrey et al., 2010). Some researchers have stated that an increase in cerebral oxygenation causes changes in the frontal lobe in the brain (Hirshfield et al, 2009; Kikuawa et al., 2008), while other researchers have mentioned a decrease in cerebral blood flow during high vigilance mental tasks (Warm and Parasuraman, 2007, pp., 146). However, changes in oxygenation in the frontal lobe and motor cortex in the brain may reflect the workload level and attentional capacity (Perrey et al., 2010). Currently, though, no study has investigated the impact of physical and mental workload together on attentional capacity by measuring brain activity (Perrey et al., 2010). Therefore, the brain activity measure could reflect the attentional resource capacity that is induced by physical and mental demands. Thus, the current study used Near-Infrared Spectroscopy (NIRS) (see Appendix A) as a neuroergonomics technique, to reflect the influence of physical and mental workload interactions on attentional capacity.

1.4 AIM AND OBJECTIVES OF THE RESEARCH

1.4.1 Research Aim

The research in this thesis derives from the importance of the task that involves physical workload and mental workload (see Appendix A) interaction issues, which may influence an individual's attentional resource capacity and performance. Therefore, the general aim of the present research was to understand the interaction effects of different levels of physical and mental workload on attentional resources (see Appendix A) along two of Wickens' (2008) dimensions, input modality (visual vs. auditory) and processing code (verbal vs. spatial), and performance based on the two mechanisms of improvement arousal (see Appendix A) and blood oxygenation changes in the brain, since the physical workload leads to more blood going to the brain (Perrey et al. 2010). It is hoped to produce a new theoretical model, which describes the influence of both types of workload on visual and auditory resources and identifies the role of physical workload in multiple attentional resources. In addition, it will help the designers of new work systems to get better human performance. This research uses four main measurements: objective measures (which were divided into measures of performance and physiological parameters), subjective assessment tools, and a new objective measure that identified the impact of workload interactions on attentional resources by determining oxygenation changes in the brain during performance of the tasks (brain activity).

1.4.2 Research Objectives

The objectives of this research, derived from the aim, are:

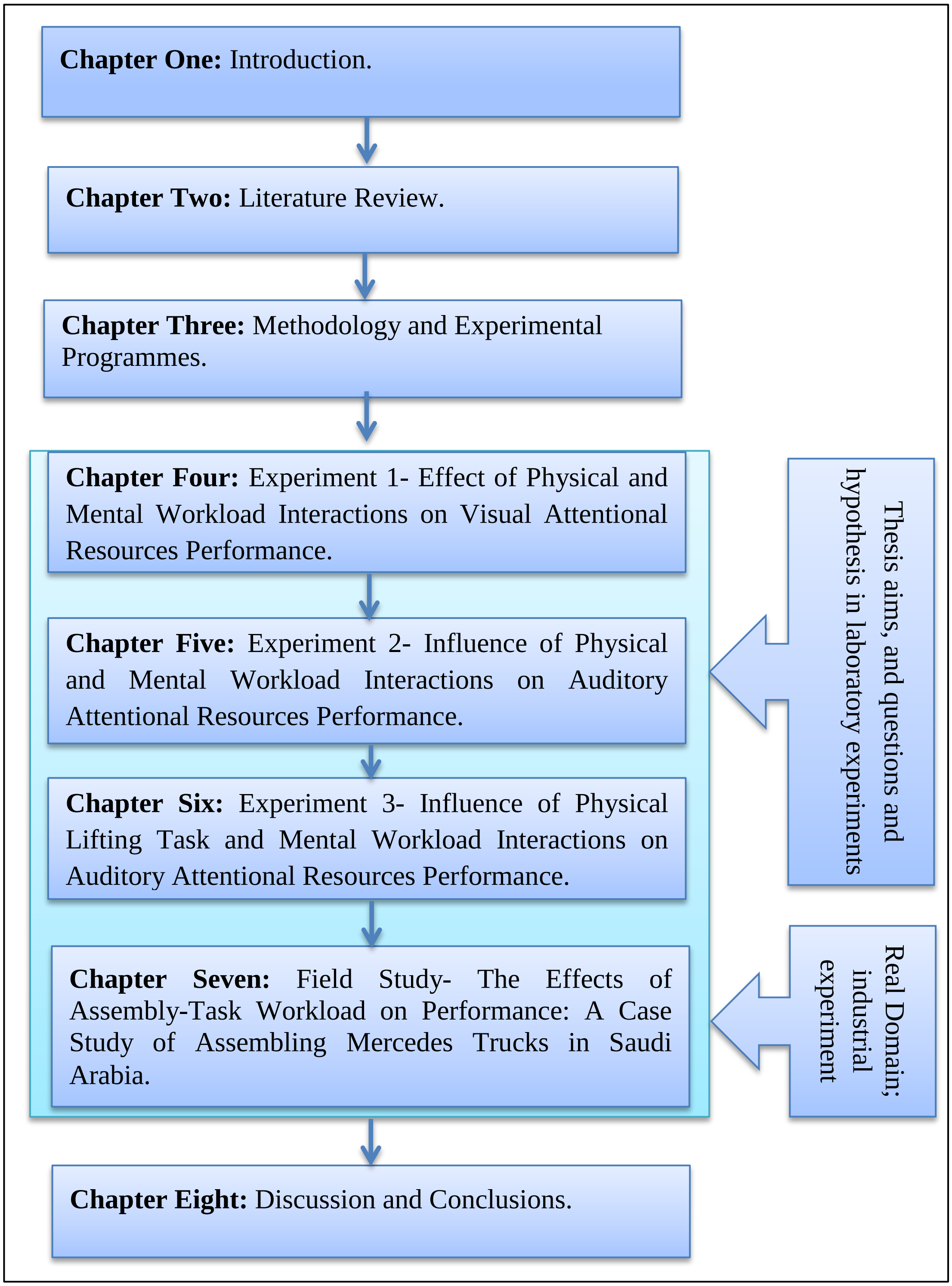
1. To review comprehensively the literature on the simultaneous effects of performing physical and mental tasks on attentional resource capacity and performance and to clarify these impacts on multiple attentional resources.

- *Use experimental studies to determine:*

2. The influence of different levels of physical and mental demands on visual attentional resources (verbal and spatial);
3. The mechanism of physical and mental workload interaction on auditory-verbal and auditory-spatial resources under different physical workload tasks;
4. The gender differences in the dual-tasks paradigm of physical and mental workload interactions.

In addition, the current thesis implements one field study as a case-study to translate the experimental setting into field setting. However, these objectives have been stated in order to achieve to the general aim of the thesis, which is to establish the impact of physical and mental workload simultaneously on attentional resource performance, in order to produce a new theoretical model regarding the influence of physical and mental demands on the attentional resource dimensions (i.e. visual and auditory, in both verbal and spatial codes). In addition to the experimental studies, the field study objective was created for a dual-task workload environment on assembly production lines to validate the model and to translate the results of laboratory-based experiments to a field setting. As well as the theoretical motivation, the research aims to arrive at valuable applied recommendations such as suggestions for redesigning the work system to balance operator resource capacity and workload levels, and for applying or improving automation systems in order to improve performance and reduce errors.

1.5 THESIS STRUCTURE



Chapter One: Introduction.

Chapter Two: Literature Review.

Chapter Three: Methodology and Experimental Programmes.

Chapter Four: Experiment 1- Effect of Physical and Mental Workload Interactions on Visual Attentional Resources Performance.

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Chapter Six: Experiment 3- Influence of Physical Lifting Task and Mental Workload Interactions on Auditory Attentional Resources Performance.

Chapter Seven: Field Study- The Effects of Assembly-Task Workload on Performance: A Case Study of Assembling Mercedes Trucks in Saudi Arabia.

Chapter Eight: Discussion and Conclusions.

Figure 1.1 Thesis outline

Chapter 1: Introduction

This chapter discusses the importance of the multi-demands job issue (i.e., those that make physical and mental demands concurrently on operators' attentional resources and performance) as an introduction to a critical issue in work system design. The issue centres around finding a balance between operator resources and the workload of the work-system; in particular, it is focused on jobs that involve both workloads concurrently, such as manual product assembly occupations. The aim and objectives of the research are specified in the outline of the thesis chapters (see Figure 1.1)..

Chapter 2: Literature Review

After presenting the introduction and scope of research in this chapter, the major terms used are task workload and the attentional resources model. Chapter 2 reviews the literature that is concerned with mental workload and is associated with other subjects, such as information processing and attentional resource theories. This is in order to explain attentional resource capacity and how it correlates with mental workload and performance. The second main part of this thesis - physical workload - is also considered. In doing so, the contribution of physical workload in the performance of mental tasks is discussed. Following that, current knowledge about brain activity in regard to workload is reviewed.

Chapter 3: Methodology and Experimental Programmes

This chapter describes the laboratory experiments in general, including interactions of the various mental and physical tasks and the conditions in which e the subsequent three experiments were carried out. Each experiment is discussed in detail in its own chapter. In addition, Chapter 3 explains the general tools and equipment used in the experiments. This chapter also includes a description of the general set-up of the experiments since the empirical methodology is similar across the three lab studies (i.e., similar conditions and outcomes measures). The distinction between these experiments is focused on the types of mental and/or physical tasks used. Furthermore, this chapter explains the field study method.

Chapter 4: Experiment 1 - Effect of Physical and Mental Workload Interactions on Visual Attentional Resources Performance

Chapter 4 presents the first experiment, which was conducted to satisfy objectives 1, 2, 4, 5 and 6. The experiment focused on the impacts of physical and mental workload on visual attentional resources (verbal and spatial). The chapter includes the experiment's hypotheses, tasks and conditions, detailed procedures, and results leading to the next experiment.

Chapters 5: Experiment 2 - Influence of Physical and Mental Workload Interactions on Auditory Attentional Resources Performance

This chapter reports on the experiment that examined the influence of workload interactions on auditory resources. It includes the experimental conditions and tasks, procedures, and findings that led to the subsequent experiment. This experiment was performed to satisfy objectives 1, 3, 4, 5 and 6.

Chapter 6: Experiment 3 - Influence of Physical Lifting Task and Mental Workload Interactions on Auditory Attentional Resources Performance

The results discussed in Chapters 4 and 5 led to the development of the third experiment, which was carried out in order to evaluate the effects of physical lifting and mental workload on auditory resources, and satisfies the same objectives as in previous chapters. This differed from experiment 2 in the type of physical task. In this chapter, lifting of boxes was chosen in order to simulate the scenario of product assembly tasks and because of its applicability to occupational settings in the real world. In addition, auditory mental tasks were selected rather than visual tasks, since it difficult to set up the lifting task and visual tasks concurrently in a laboratory environment.

Chapter 7: Field Study - The Effects of Assembly-Task Workload on Performance: A Case Study of Assembling Mercedes Trucks in Saudi Arabia.

This chapter presents the details of a field study carried out in Saudi Arabia, on a truck assembly line. This study was carried out in order to validate the theoretical model identified by the laboratory experiments and satisfies objective 7. Additionally, it provides a number of recommendations regarding assembly factories that could improve the design of such work systems.

Chapter 8: Discussion and Conclusions

This chapter presents a summary of the work, the overall results, and discussions from all laboratory experiments and findings. It also presents the new theoretical model that emerged from these laboratory experiments. In addition, it reports the main results and discussion of the field study, and the emerging applied recommendations. A main conclusion is drawn and suggestions for further work in this research area are proposed.

CHAPTER 2: LITERATURE REVIEW

2.1 OVERVIEW

A relationship between physical and mental workload and task performance exists. Achieving a balance between dual-task demands and an individual’s attentional resource capacity is key factor in work-system design needed in order to improve productivity and reduce errors (Mozrall and Drury, 1996).

The key themes in this chapter are a review of the meanings of two terms: multitask workload and attentional resources. Most studies to date have examined the impact of dual task mental workload on attentional resource capacity (Wickens, 2002). However, in this thesis, the term ‘multitasks workload’ refers to mental and physical interactions. ‘Attentional resources’ refers to the multiple resources model along two of this model dimensions: input modality (visual vs. auditory), and processing code (verbal vs. spatial) (Figure 2.1), which represents the outline of the literature review and shows how this review covers mental workload and information processing theories, in order to clarify the correlation between mental workload and performance. The chapter then focuses on the relationship between physical and mental workload and individual performance. Therefore, this chapter clarifies the interaction of physical and mental workload based on previous theories. Each section of the review will be examined.

This chapter clarifies the correlation between the attentional resources of physical and mental workload. In addition, it covers the way in which physical workload can affect cognitive functions during the performance of a task. Mental and physical workload measurements are also discussed in detail in order to illustrate the combined measurements for overall workload, which leads the author to the use of a novel combination of measures that reflect the impact of both physical and mental workload on physiological arousal and attentional resource capacity. These results highlight the limitations of previous research on the physical and mental demands of individual performance and bridge the gaps in ergonomics literature. These were derived in order to lead to a new model that describes the valuable contribution of physical and mental workload interactions in the dual-task paradigm on individual attentional resources, and this model was investigated and validated later, in subsequent chapters of this thesis.

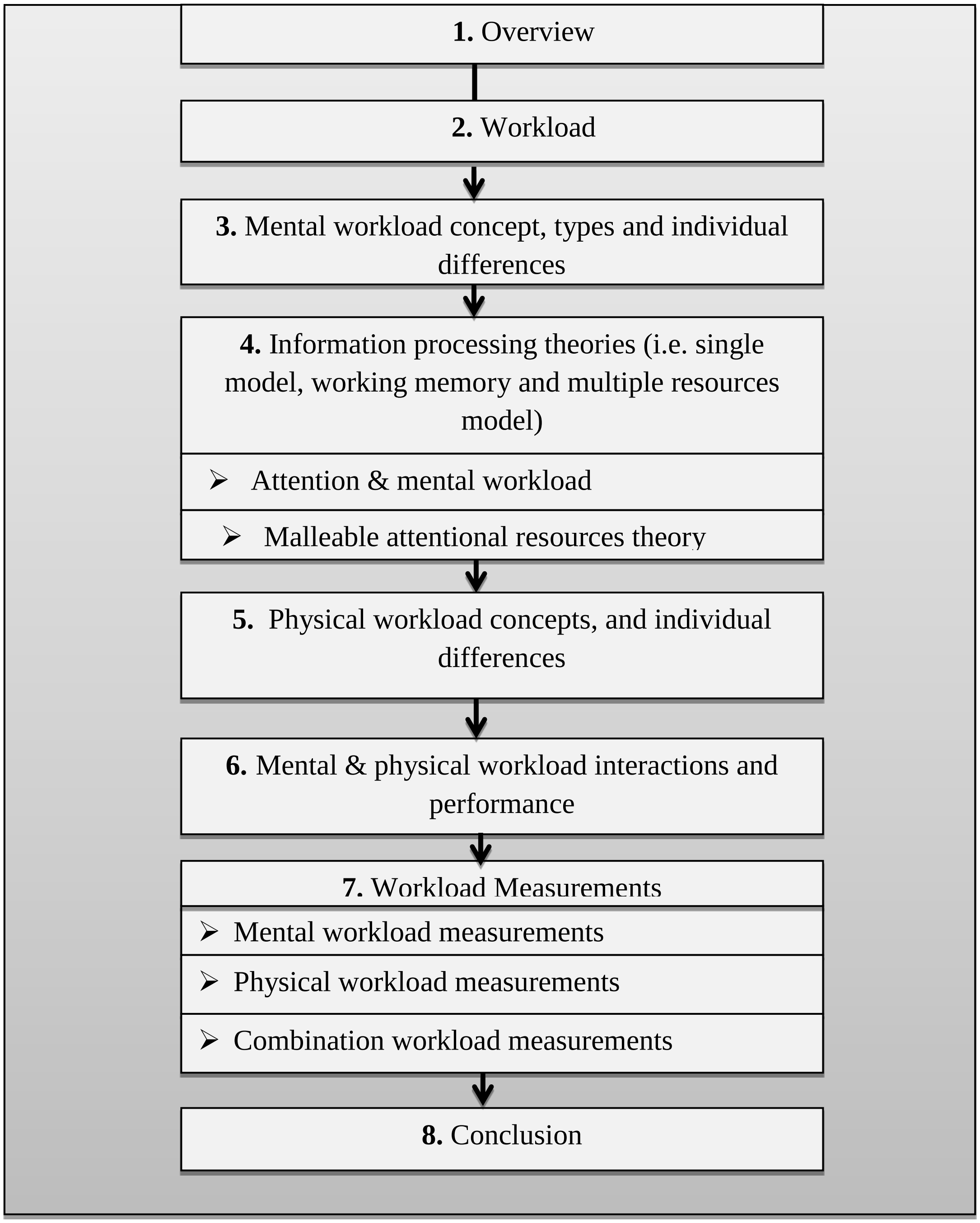


Figure 2.1 Literature review outline

2.2 WORKLOAD

Workload factors are the main task characteristics that influence human performance. These factors can be defined as how an operator completes the required work (i.e. capacities) and how the operator understands the task (i.e. task demand) to meet the operating system's demand (Megaw, 2005). Task demand is the proportion between the time needed (TR) to do a certain task and the time available (TA) for workers (Wickens et al., 2004). According to Rouse et al. (1993), workload is the demand of a job that the operators should satisfy to achieve the goal. Wickens et al. (2002) wrote that workload is a combination between the available resources of an operating system, task demand, and workers' capabilities.

Cox-Fuenzalida (2007) reported that workload affects and reduces the ability of workers. Generally, an increase in the task demand level may lead to a decrease in correct responses and an increase in response time (Cox-Fuenzalida, 2007). Also, he stated that the high-task workload and task complexity are considered to be two of the most important aspects in reducing the quality of worker responses. As a result, the overload workload increases operator errors increase in job that require both workloads mental and physical since, the high physical workload leads to increase the arousal level.

In fact, mental workload has increased more than physical workload in many jobs due to the rapid increase in technology. However, most tasks in the real domain still make both physical and mental demands on the operator. Workload is divided into two main parts: mental workload (i.e. perception, monitoring and decision-making) and physical workload (i.e. lifting parts, pushing and material handling). In a dual-task situation, the physical loads could place stress on cognitive task performance. Thus, it is necessary to find a balance between available resources (system and operator capabilities) and task requirements in order to avoid degradation in both worker and system responses. Furthermore, measuring workload is useful in determining task demand and helps designers select a suitable type of workload metric (Tsang, 2001).

Indeed, the task workload that includes physical and mental workload is more difficult to control than one that requires either physical demand or mental effort but not both. For example, in combination the levels of physical workload should not exceed the individual's capacity (Sluiter, 2006) and, similarly, the mental workload should not be greater than the individual's attentional resource capacity (Wickens, 2002). Furthermore, any physical activity during job performance can place a load on attention due to the impact on the cardiovascular system and the physiological arousal state of the operator. As a result, the balance between overall workload and individual cognitive functions capacity is important and not simple, since any intensity increase in physical workload can lead to poor performance and injuries (Perrey et al., 2008). Thus, the control of single task workload (i.e. physical or mental demand) is easier than control of a task that requires physical and mental effort. For instance, a high level of physical workload can influence the information process through high increases in physiological arousal that, in turn, decrease attentional resources' capacity. According to Young and Stanton (2002[a]), the relation between mental workload and performance is U-inverted as is the relation between arousal and performance. Furthermore, physical activity supplies more blood to the brain so the amount of oxygen that is delivered to the brain also increases and improves and facilitates the information process (Antunes et al., 2006). Therefore, task workload is a key determinant of human performance. It may include physical and/or cognitive components, and these can interact to influence operator performance.

Therefore, it is important in this PhD thesis to consider the impact of physical and mental demands on individual performance. The next sections discuss mental workload concepts and mental workload models. After that, this chapter discusses physical workload concepts and the theoretical background regarding the interactions of physical loads on cognitive tasks. Finally, the literature presents a detailed discussion on workload measurements, which includes mental workload evaluation techniques, physical workload assessment methods and joint measurements of both workloads.

2.3 MENTAL WORKLOAD

In recent years, the increasing level of automation in most operating systems in different jobs has placed more emphasis on the mental workload (MWL) of operators (Megaw, 2005; Neerincx et al., 1996). Furthermore, MWL has been documented as a necessary aspect in human performance within high-technology and complex operating systems (Xie and Salvendy, 2000). Generally, it is essential to note that there are considerable differences between the opinions of ergonomics researchers about the definition of mental workload for humans in the workplace (Xie and Salvendy, 2000; Hwang et al., 2008). Indeed, mental workload is the communication between the framework of system, resources, and worker limitations and capabilities (Kramar, 1991).

Charlton and O'Brien (2002) said that mental workload is, "the amount of cognitive or attentional resources being expended at a given point in time" (p. 98). Put another way, mental workload demands that the operator uses some cognitive functions such as vigilance, concentration, decision-making processes, memory processes, or attention (Sluiter, 2006). In the current thesis, the term "mental workload" refers to the amount of attentional resources that are needed to complete a task and that can be affected by operator characteristics (e.g., experience, training, attention, and skills) and task features such as task load and procedures (Young and Stanton, 2004) (Appendix A).

Mental workload comprises two major parts: "stress (task demand) and strain (the resulting impact upon the individual)" (Young and Stanton, 2004, p. 39-1). They said that mental workload is a percentage of the resources needed to meet operating system demand. Mental workload includes different tasks: decision-making, monitoring, perception, and calculation (Perry et al., 2008).

There are some aspects that affect attentional capacity and MWL of workers, such as age, arousal, or mood state (Young and Stanton, 2002[a]). Neerincx and Griffioen (1996) said that changes in the state of workers may impact their mental capacities and influence task performance. Most studies have shown that a high or low level of arousal leads to unacceptable performance and high numbers of errors. An intermediate level of arousal maintains performance at an optimum level (Neerincx and Griffioen, 1996). Arousal can be defined as the overall state, level of activity, and behaviour of an individual in response to different environmental stressors (e.g. task workload) that activate the nervous system (Matthews et al., 2000). There is an inverted-U relationship between arousal and performance as well as the relationship between mental workload and performance (Young and Stanton, 2002[a]). An increased mental workload increases physiological arousal, which in turn increases attentional capacity (Young and Stanton, 2002[a]). However, if the mental workload is increased too much, the level of performance decreases due to high arousal level (Wickens and Hollands, 2000). However, Hwang et al. (2008) found that the correlation between mental demand and performance is not a curved line. The reason for decreasing performance under very low mental demands is discussed later in *Malleable Attentional Resources Theory* in section 2.4.4.

Some direct factors may impact the level of arousal, such as environmental factors (noise, vibration, and lighting) and personal problems (Xie and Salvendy, (2000). Mental workload is not only influenced by task demand, but is also affected by operator factors (e.g., experience and skill) and individual differences (Young and Stanton, 2004; Xie and Salvendy, 2000).

According to Wickens (2008), mental workload can impact on attentional resource capacity and lead to performance decrements. Increasing levels of difficulty in mental tasks will lead to performance deterioration. Also, according to Young and Stanton (2002[a]), mental underload may lead to poor performance, just as mental overload. Thus, it is necessary to find a balance of available resources (system and operator capabilities) and task requirements, to avoid degradation in both worker and the system responses. The next section explains the impact of overload and underload situations on individual performance.

2.3.1 Mental Underload and Overload

High-technology systems can impact MWL in different directions; such that they can increase it (overload) or decrease it (underload) (Wilson and Russell, 2003; Young and Stanton, 2002[b]). Young and Stanton (2004) said, “Mental overload and mental underload are therefore very real possibilities, and both are equally serious conditions that can lead to performance degradation, attentional lapses, and errors” (p.39-2). The findings of the impact of mental workload on individual performance are not uniform. Some researchers have stated that the relationship between mental demand and operator performance is an inverted–U shape based on the curvilinear correlation between arousal and performance (Wilson and Russell, 2003; Young and Stanton, 2002[c]), whereas other researchers have documented that the relation is linear (Hwang et al., 2008; Lee, 2001). However, it seems that depend upon the level of low mental workload since, the too simple cognitive tasks will keep the arousal at too low level by increasing level of trust against the task also, the variations in the previous researches results may be refer to the type of cognitive task and complexity.

It has been reported that increasing levels of mental demand lead to greater errors, whereas low mental demand does not. For example, Hwang et al. (2008) found that by increasing the levels of monitoring various parameters under three different levels of difficulty in a control room at a nuclear factory, a high level of viewing tasks (monitoring specific parameters under high flow speed) increased error rates, but they concluded that there is no performance decrease with mental underload level. This finding is similar to Lee (2001), who found that increasing the number of speakers in a tone localisation task leads to performance decrements (in a linear correlation).

On the other hand, according to Young and Stanton (2002[c]), the danger of very low mental demand is the same as that of mental overload. Also, they said that low mental demand reduces attentional capacity, which may lead to unacceptable performance. They found that increasing levels of automation in a driving task reduces mental demands and leads to poor performance. They also noted serious performance problems were manifested in any sudden event while performing in conditions of underload, since, under normal workload conditions, an individual can more effectively deal with an emergency event because the state of attention is high. These results are consistent with Wilson and Russell (2003), who reported that increasing or decreasing mental workload results in performance declines.

As mentioned previously, this highlights the importance of a balance between a task's mental workload and the dangers of mental underload and overload. Mental task performance depends upon differences among individuals as well, including gender differences in strategies for performing mental tasks; the present research is concerned with gender differences, as individual differences can cause a variation in mental task performance. It is therefore necessary to address the impact of gender differences as an individual aspect of mental performance.

2.3.2 Individual Differences and Cognitive Performance

Individual differences in mental ability exist; some individuals perform mental tasks better than others. These abilities depend upon various factors such as skills, knowledge, age, and gender (Matthews et al., 2000, p.241). For example, the impact of skill on working memory has been confirmed, since faster learners are better than slower learners in terms of memory storage, perhaps because of better 'chunking' skills (Wickens and Hollands, 2000). The important issue for this study is the individual differences in cognitive performance that appear as a result of differences in attention allocation (Engle, 2002).

One of the factors that have an impact on cognitive tasks is gender. In general, there are no significant differences between males and females in intelligence tests, but there are differences in other tasks (Halpern, 2000). This depends significantly upon the type of mental task and its complexity (Matthews et al., 2000). To date, studies that have investigated the impact of this factor on complex task workload have been rare (Matthews et al., 2000).

2.3.3 Verbal and Spatial Tasks Against Gender Differences

Performance variations between men and women on verbal or spatial tasks have been examined in several studies (Hyde et al., 1990; Voyer et al., 2006; Peters and Battista, 2008). Most of these studies used a simple visual or auditory mental task (e.g., reaction time tasks) (Spierere et al., 2010). Generally, men are superior in spatial processing, whether on auditory or visual tasks (e.g. mental rotation tasks and motor aiming tasks), whereas women are better at verbal tasks (number, mental arithmetic and word tests) (Koscik et al., 2009; Spierere et al., 2010). These differences are related to various factors such as the strategy men use in processing the orientation of spatial figures and genetic differences in brain structure (Koscik et al., 2009; Skrandies et al., 1999).

However, the results of experiments in gender difference studies are not uniform; some studies have found differences in the accuracy and response time between men and women in some mental tasks (Voyer et al., 2006), whereas other researchers have found no significant differences between the genders (Halpern, 2000). For example, it has been stated that women outperform men in verbal tasks such as word tasks and mathematical problem-solving, whereas men are better at visuospatial tasks, such as a task involving a flashing light on a screen and tasks that require cognitive transformation (Spierere et al., 2010). In contrast, Skrandies et al. (1999) found no significant difference in reaction times between men and women in visual arithmetic mental tasks. According to Hyde et al., (1990), the gender difference in cognitive performance was small and decreased over the course of a year (Feingold, 1988; Hyde et al., 1990). These differences depend upon the type of mental task and their difficulty (Spierer et al., 2010; Voyer et al., 2006).

In general, the difference between men and women in spatial attention ability tasks depends upon the type of spatial task (Halpern, 2000; Spierere et al., 2010). An earlier literature review reported that female participants achieved low scores compared with men on several tests involving visuospatial ability (Money's Road Map Test; Geometric Forms and Mental Rotation Test) (Matthews et al., 2000; Halpern, 2000).“Verbal ability” does not have a uniform definition like other cognitive abilities. Verbal tasks could include the ability to remember a word, a speech task, vocabulary, and verbal analogies, as well as arithmetic ability. Generally, in verbal tasks women get higher scores than men. Halpern (2000) mentioned that “there is little doubt that females score differently from males on mathematical tests” (p.112), according to a review of previous papers related to gender differences in arithmetic abilities. Moreover, gender differences in mathematical problems depend upon the level of ability of both men and women. For example, huge gender differences are apparent when very talented men and women are compared, whereas these differences become small when only moderately talented participants of both genders are compared.

With regard to auditory tasks, few studies have examined gender differences, especially in audio-spatial task performance and complex hearing attention tasks (Yagi et al., 1999) such as a localisation task (Zundorf et al., 2011). Zundorf et al. (2011) examined the impact of a sound localisation task on audio-spatial resources in detecting a target sound (cocktail parties; audio-spatial task), and the results indicated that men were better than women at capturing the correct sound from a multi-speaker environment. In contrast, the differences disappeared in the single-speaker task condition. The authors mentioned that gender differences in spatial ability could be related to brain asymmetry. They concluded that men are superior in their strategy of attentional allocation in extracting spatial information in a scenario involving multi-sound sources. Generally, men outperform women in auditory spatial reaction time tests, whereas women are better at audio-verbal tasks, as with visual tasks. As previously discussed, it appears to be important to examine the gender factor in the current PhD thesis in order to understand how both genders use their cognitive abilities during physical activities (i.e. dual-task scenarios).

After reviewing in previous sections the mental workload concept and how gender difference factors can affect mental performance, and before moving on to the second part of this literature review, which examines physical workload and the contribution of it in cognitive functions, it is important to discuss the foundation and development of mental workload models. Thus, the following discussion addresses information processing theories to understand the developments in these theories that deal with correlations between mental workload and attentional resource capacities. In other words, this discussion will illustrate the ways in which cognitive task performance is impacted by increasing or decreasing levels of mental task workload.

2.4 OVERVIEW OF INFORMATION PROCESSING

This section aims to clarify mental workload models and theories. In addition, it aims to present the models that explain mental resources and the impact of mental workload on these resources, and how the authors have not considered physical resources, and therefore the dual tasks of physical and mental workload on attentional resources have received less attention.

The information processing flow while performing single- and dual-task mental demands has been studied in depth. Numerous attention theories have been developed to describe information processing under selective and divided attention resource mechanisms and the capacity of individuals’ cognitive resources (Wickens, 2002). For example, simple models of memory information processing involve three main stages that the information goes through: sensory registry, short-term memory and long-term memory (Baddeley, 2004). All of these are integrated together to complete the psychological process (Wickens and Hollands, 2000).

However, to perform cognitive tasks, an individual needs to engage in a different cognitive information process. Cognitive tasks include prescription, decision-making, reasoning and problem-solving. There are two types of scenarios in task performance: the single-task or dual-task paradigm. All individuals have a different amount of cognitive capacity, and they cannot perform in an acceptable way without a balance between their resource capacity and task demands (Engle, 2002; Wickens, 1980). Furthermore, individuals are required, in some situations, to increase the attention process, especially while performing separate tasks concurrently, since they need to divide their attention (time-share) to maintain good levels of performance in both tasks (Wickens and Hollands, 2000). Therefore, psychologists have developed several theories to explain the information processing structure during task performance, and they have become more focused on the capacity demands of different tasks (Reed, 2007, p.1). However, all these models try to understand how individual attentional resources work under different mental workload conditions. But none of these theories have considered the other dual-task paradigm situation which is common in the real domain: the situation reflected in the task that requires physical effort as well as mental demand. Thus, to bridge this gap, this thesis investigates the effects of physical load interactions with mental demands on cognitive capacity.

The completion of numerous tasks in the real domain requires a mental operation process. These tasks include different levels of cognitive demands, and they need a certain level of attention, especially in a dual-task paradigm. Furthermore, each individual has limited cognitive attentional resources. The function of selecting these limited resources is not done automatically to perform mental tasks (Wickens and Holands, 2000; Wickens, 1980). The most important stage in information processing is attentional allocation, or dividing attention, since it depends upon the strategy of the individual as to how s/he divides his/her attention while performing tasks concurrently; thus, increasing levels of attentional workload in time-shared tasks can lead to performance decrements in one of the tasks.

Therefore, many theories have been posited and developed to explain the mechanism of information processing while performing cognitive tasks. Also, these theories have attempted to identify the attentional resource capacity, and psychologists have performed several studies to investigate the impact of single and multiple task demand on task performance. Some background is provided below regarding these models and theories, before discussing the mental and physical workload literature.

2.4.1 Attention and Single Resource Theory

Decades ago, various theories were developed to describe information processing in the human brain, to show the value of memory in performing cognitive tasks and the limitations of working memory capacity. The classic model of single resources is the Kahneman (1973) model, which explains the capacity model of attention with respect to the effect of high mental workload on the memory system; this model used as an alternative model to the bottleneck or filter theories (Reed, 2007, p.53; Young and Stanton, 2002 [b]). Essentially, there is a distinction between the bottleneck theories and the capacity model theory in the interference of information (stimuli) happening while performing tasks simultaneously, whereas both theories are identical in expecting that concurrent tasks can interfere with each other (Reed, 2007). The single-resource theories assume that individuals have limited capacity. The capacity model posits that exceeding the capacity limits, by performing concurrent tasks, leads to interference, and a decline in performance.

Generally, control over attentional allocation is very important. The Kahneman model of attention demonstrates that individuals can control and manage attentional processes through a strategy for resource allocation while performing concurrent tasks. The main point of the capacity model theory is that performance suffers when there is not a balance between the required demands of the two tasks in hand and the individual attentional resources limit (Baddeley, 2004; Reed, 2007). Task performance depends upon the relation between the amount of cognitive resources that are available and the amount of resources that are required to complete the task at hand. Therefore, in the dual-task paradigm, if the amount of resources required by the task is lower than or similar to the amount of available resources, task performance will be acceptable.

In terms of task performance, Norman and Bobrow (1975) found that the performance of an individual depends on two parameters: the quality of the data and resource limitation. They stated that performance cannot improve even when high levels of resources are consumed in the task when the quality of the data input is too poor; this process is called data limitation. This means that performance improves as data input improves; it is not related to the amount of resources that are spent. On the other hand, if a great deal of resources are consumed and performance changes, this is called resource limitation. However, the researchers suggested that, in performing concurrent tasks, if the overall workload exceeds the attentional resource limits, performance will fall due to task interference (Young and Stanton, 2002[b]).

According to Young and Stanton (2002[b]), there is a fundamental weakness in the single-resource theory in a multitask condition, such that it is predicted that task performance will suffer due to the difficulty of manipulation when the individual is performing two separate tasks simultaneously (time-shared). The authors found that time-shared tasks were not impacted by the difficulty of manipulation and that performance was good in both tasks (see, Wickens, 1980, pp. 239; Wickens, 1992). As a result, the multiple-resources model was created (Young and Stanton, 2002[b]). This model can explain many of the impacts of structural alteration in task workload on task performance; in contrast, the single-resource theory cannot do this since it has a limited capacity (Wickens, 2002). This may be because the distinction between resource pools is understood by the multiple attentional resources model. An explanation of this model will be provided in section 2.4.3.

All the research discussed so far has focused on single resource models and mental workload; it has considered attentional capacity while the individual performs a single task or multiple cognitive tasks, but has not investigated physical and mental tasks concurrently. Consequently, testing physical workload on attentional resources will be more valuable and interesting as a new model that explains the workings of cognitive resources during physical work.

2.4.2 Working Memory Model

Baddeley and Hitch (1974) proposed a new model for the short-term memory, single-resource system with a working memory model (multi-store model). They claimed that the existing short-term memory model was overly simplistic. Since, according to Baddeley (2004), the information processing flow is simple, the information comes from environmental sources to the sensory memory (visual and auditory). However, working memory (WM) is a set of operations and storage that reflects the brain's processes while performing cognitive task learning, decision-making and reasoning (Eysenck and Keane, 1990, p., 133; Baddeley, 1992). In other words, it governs the ability to recall information held in the brain to complete cognitive tasks. Thus, there is a difference between working memory and short-term memory, since WM can store and process information concurrently, while short-term memory is used to hold information temporarily (Baddeley, 2004).

The main component of working memory is the central executive component; the major function of this part is to control and regulate the information and locus of attention that come from the resources (input) with respect to appropriate resources that are needed to complete a cognitive task, so this component manages information transfer from/to other components of the system, and it connects these components with long-term memory. Working memory includes two other components besides central executive (Reed, 2007): the visuospatial sketch-pad and the phonological loop. It is necessary to mention that WM serves as temporary storage for information between the sensory and long-term memory, and this storage is characterised by limited capacity (Eysenck and Keane, 1990, p., 133).

However, given that all of the components in the working memory model have a limited capacity; numerous authors have studied and tested working memory capacity during different types of mental tasks and concurrent cognitive demand situations (Baddeley, 2003; Engle, 2002). They used different types of cognitive tasks to evaluate WM capacity, such as a reading-span task, an operation-span task and a counting-span task (Engle, 2002). In general, humans need a certain level of cognitive capacity to complete task demands (single or concurrent tasks). The task demand includes two types of workloads - mental and physical - and each task requires a certain level of mental capacity. Therefore, the central executive allocates suitable attentional resources to complete the task at hand.

The dual-task scenario and working memory capacity issue have been extensively studied (Baddeley, 2004). In dual-task conditions, memory capacity works to divide the two tasks. For example, if the workload requires two separate resources, then priority will be allocated to the more important task and this situation is easier than if the task needs the same attentional resources. In other words, if the task requires the same storage resources, then the importance switches to the primary task, while the other task will be considered as a secondary task (Baddeley, 1992; Wickens, 1980). As a result, an increasing level of workload complexity will switch the attention of the individual to the main task and the performance of the second task will suffer. The central executive is the controller in this process, so any excess information load on the available capacity limit will be unnoticed.

2.4.3 Multiple Resources Model (MRM)

The multiple-resources model (MRM) was conceived as a response to some observed disadvantages with single-resource theories of attentional capacity as stated previously, particularly in the dual-task approach, since these theories expected that an individual could not simultaneously perform two separate tasks as well as they could perform one task (Wickens, 1980, 2002). MRM proposed that dual-task interference will increase only when both tasks require the same attentional resources;

conversely, task performance can be preserved if the tasks use different resources – hence multiple resource pools. MRM is related to an important concept in engineering psychology: attention and workload. Attention is connected to dual-task performance since, good divided attention can lead to better dual-task performance, particularly if the two tasks require different resources (Wickens, 2002). For instance, if two tasks require similar attentional resources (e.g. visual or auditory), performance may suffer (Wickens, 2002). This is especially true if one of the similar tasks is more difficult than the other (Wickens, 2008). However, the attention also, is connected to awareness, and variations in concurrent task performance. On the other hand, the workload concept relates to the resource issue while performing a task with a high workload (Wickens, 2002). Recently, the workload concept has been related to mental underload when the task workload becomes too low (Young and Stanton, 2002[c]). Therefore, this theory is sometimes called a workload theory since it expects performance to decrease under overload.

Resource theory describes multitask interference in terms of the loss of energy for information processing (Matthews et al, 2000; Wickens, 2008, 2002). The multiple attentional resources model includes four dimensions (see Figure 2.2). The first of these components is the processing stage (perception, working memory, and responding; this dimension includes the resources that are responsible for resource selection, central executive function (working memory), and response function). Interference between the resource workload of mental tasks and perceptual activity in the working memory storage function and data conversion function can be predicted by the stage dimension of the model (Wickens, 1988). Second, responses dimension is related to the processing stage dimension. Information in the stage dimension is separate depending upon the selection attention and execution of responses, which includes vocal and manual responses. This dimension parallels the codes dimension. Third, processing codes involve two types of resources: spatial and verbal. This dimension increases the efficiency of performance (response dimension) in dual-task performance since it makes a distinction between verbal and spatial resources and deals with the information depending upon its type in a separate resource. The final dimension is input modality: auditory or visual. Wickens (2002) added a new dimension to the MRM model within the visual channel, to reflect the distinction between focal and ambient vision as separate resources and with separate capacities. The benefits of these separate resources (a) enhance time-sharing, (b) characterise the information used by different brain structures, and (c) allow different qualitative visual information processes. However, ambient vision is not exclusive, and it is used for orientation information. Conversely, focal vision is used to identify finely detailed patterns such as small figures or reading text.

According to Wickens (2002), the verbal and spatial resources in this model relate to different types of data, whether in the perception stage, working memory or response dimension, and each of these resources has a different upper limit. Third, with respect to perceptual modalities (visual and auditory), in some tasks the individual needs to divide his attention between two main dimensions - the ear and eye - rather than using only one of them (Alais et al, 2006). This is called cross-modal time-sharing when the individual uses different resource modalities in a dual-task condition. In contrast, when the individual uses the same perceptual modalities to perform two separate tasks concurrently, it is called intra-modal time-sharing (Wickens, 2002; Wickens and Liu, 1988).

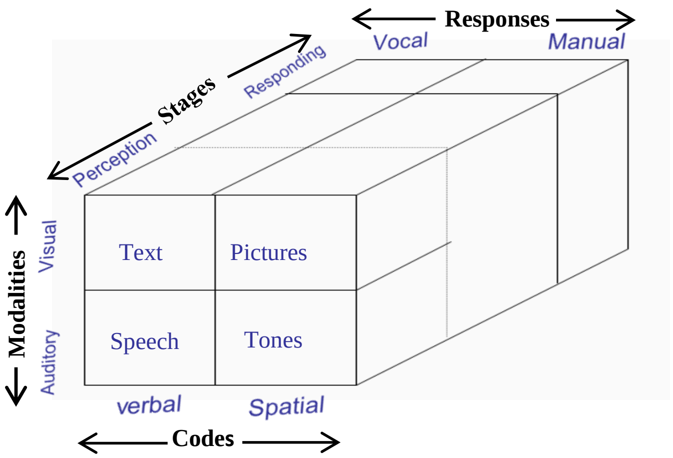


Figure 2.2 The proposed framework of multiple attentional resources. (Wickens & Hollands, 2000)

In general, there are some differences between attentional resources and working memory, but the distinction is vague since both models contain similar mechanisms

(Young and Stanton, 2002^b). Information from a source associated with verbal or spatial tasks is coordinated and controlled by the central executive in working memory (Young and Stanton, 2002^b). However, the use of multiple resources can be defined as “moving the locus of attention from sensory and perceptual input to central processing and even response execution” (Young and Stanton 2002^b, p.181). They also noted that this function of attentional resources is categorised in the region of working memory.

Verbal and spatial codes are a part of the multiple resources model, so information processing enters memory through different resources, which are related to the task type: verbal or spatial (Matthews et al., 2000). The processing of separate tasks depends on their type, whether verbal or spatial, and is a result of integration between the experience and type of task (Wickens, 2002).

The MRM suggests that information processing flows from the sensory input to the processing stage through particular channels depending upon on the type of information and the type of task (verbal or spatial) (Wickens, 1980, 1984), since the model suggests that humans have different resources for information processing instead of a single resource while performing different tasks simultaneously. An individual can interact with more than one task at the same time (time-shared) and the performance of the individual depends upon the capacity limit of each resource (Wickens, 1984, 2002). For example, many previous studies have examined the impact of workload difficulty on attentional resource capacity using primary and secondary tasks. They confirmed that increasing difficulty in the primary task leads to decreased secondary task performance, since resources have a limited capacity. Therefore, if the amount of resources required to complete a task exceeds the upper limit of available resources, performance will suffer.

Furthermore, if both tasks require the same resources (i.e. visual or auditory), dual-task performance will be more problematic than if the two tasks consumed different resources. Finally, variation in the performance of multitask demands does not depend on the quantitative resources required for one or both tasks, but rather is related to the prioritization of attentional division between the two tasks (Matthews et al., 2000).

In the dual-task condition, variations in performance can occur due to variations in the level of mental workload of both tasks if the workload level is within resource capacity limits (Matthews et al., 2000). As regards attentional resources, an increasing workload level can affect an individual's strategy of attention allocation, so it may impact performance (Wickens, 2008). Furthermore, in duall-task conditions, the individual's strategy in allocation policy can impact on performance, since the individual needs to consider how to manage his/her attention and effort for a particular activity or resources (Wickens, 2008). There are two detrimental mental workload conditions: excessive mental demand and inadequate task demand, both of which can lead to decreased performance. Cook and Salvendy (1999) noted that, when the level of mental workload increases, the duration of task performance increases. Nor is a reduced task workload always the best way to maintain operator performance because some tasks involve extreme conditions that may cause mental underload or overload for the workers (Young and Stanton, 2002[b]). Indeed, the seriousness of the impact of mental underload on performance is the same as the effect of overload; both can lead to unacceptable responses (Hwang et al., 2008; Young and Stanton, 2002[b]). Consequently, researchers have created a new theory to explain performance decrements in mental underload conditions due to the shrinkage in attentional resources (Young and Stanton, 2002[b]); the next section, 2.4.4, explains this theory.

2.4.4 Malleable Attentional Resources Theory (MART)

As mentioned above, mental underload has a negative impact of on performance due to a reduction in attentional resources, especially in automated work systems. Thus, the malleable attentional resources theory (MART) emerged to describe performance failure due to a significant reduction in the level of attentional resources that happens due to low mental workload (Young and Stanton, 2002[b, c]). In fact, the increasing technology used for some tasks can lead to a decrease in MWL. Indeed, high-technology systems can impact MWL in different ways, increasing it (overload) or decreasing it (underload) (Hwang et al., 2008; Young and Stanton, 2002[b]). Previous studies have suggested that too great a cognitive task load can decrease individual performance due to overload (Wilson and Russell, 2003; Xie and Salvendy, 2000; Young and Stanton, 2002[b], 1997). The negative effect of mental underload on task performance has been investigated previously in various papers, but the reasons for performance decrements in underload circumstances are still unclear (Young and Stanton, 2002[b]). Hwang et al (2008) mentioned that individual performance can decrease under a low level of mental demand over a long time period because the individual cannot maintain a good level of situation awareness.

In fact, task workload can impact attentional resources in two ways (Wickens, 2002, 2008). First, if the task workload is too high (exceeds the resource capacity), performance will decrease. Second, if the task demand becomes too small compared to the attentional resource limit ("residual capacity"), it will lead to poor performance. The "residual capacity" is the amount of resource capacity that is not used in the task performance (Wickens, 2008, p. 453).

Most research studies that have examined the impact of mental demand on attention have assumed that resource capacity limits are fixed (Wickens, 2002). However, there are some factors can influence resource capacity, such as arousal and mood (Kahneman, 1973; Reed, 2007), and these factors are considered to be in a fixed state in all these studies (Young and Stanton, 2002[b]). Performance, in most of these studies, depends upon the load of the primary or secondary task that is related to the task conditions. Therefore, an alteration can occur in a comparatively short time due to this limit, and this alteration depends on the task condition (Young and Stanton, 2002[c]). As a result, Young and Stanton developed the *malleable attentional resource pools* model (2002[c]). They concluded that improving a work system by reducing the required demand is not always a good idea since, according to their assumption, a drop in attentional resource capacity occurs to accommodate the reduction in task demand, contrary to the principle stating that "work expands to fill the time available" (Young and Stanton, 2002[c], p., 186). As stated in previous studies, variations in individual performance depend on the changes in task workload levels, since when the task workload increases, the amount of effort increases to keep performance at an acceptable level.

As mentioned in previous sections, according to attention theories regarding resource capacity, it has been assumed that the individual has a fixed capacity and that performance decreases when the resources required for task workload exceed the upper limit of available resources. In addition, the theories assume that performance is data-limited; here, performance depends on the quality of data available (Norman and Bobrow, 1975). Figure 2.3 shows the correlation between performance and task demands; some researchers have found that individual performance will decline only when the amount of task resources exceeds the available attentional resource capacity (see, Liao and Moray, 1993; Liu, 1996), which is consistent with the fixed-capacity model concept. The supposition of these studies is that the demands of the primary and secondary tasks (multitasking studies) are similar. However, in dual-task studies, it is necessary to mention that good performance on a secondary task could mean that the level of workload for the primary task is low.

MART assumes that, across a range of task loads, performance is resource-limited (Young and Stanton, 2002[b]). Therefore, some studies have found that the correlation between performance and mental task demands is an inverted-U (see Neerincx and Griffioen, 1996; Wilson and Russell, 2003; Young and Stanton, 2002[c]). However, according to MART, performance will decline under low mental workload due to the shrinkage in attentional capacity, and it will suffer under high mental workload due to exceeding the upper limit of attentional capacity. In contrast, it will be optimised at an intermediate level of mental tasks; these ideas are illustrated in Figure 2.4. Generally, MART assumes that the relation between performance and mental workload is an inverted-U. This correlation is the same as the one between physiological arousal and performance (Wickens and Hollands, 2000). MART states that a slow increase in task demands will facilitate performance; thus, an individual can respond to any unexpected action, so the individual can then make a good response while performing a task with a high workload, since the attentional capacity has increased. In contrast, this response will be poor under a low level of mental workload due to resource reduction.

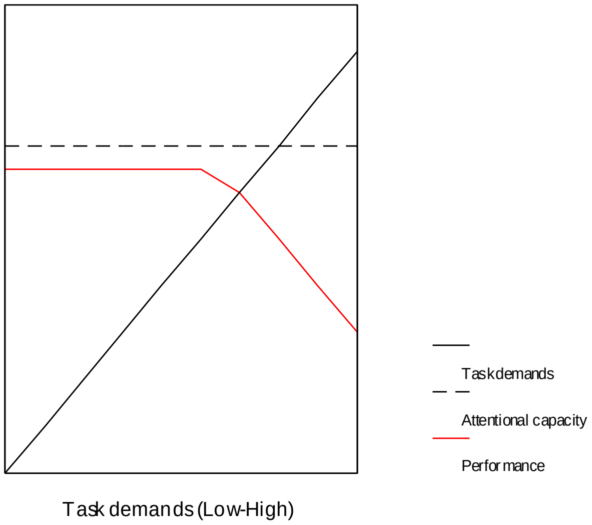


Figure 2.3 Performance against task demand under a fixed-capacity model (see Young and Stanton, 2002[b]).

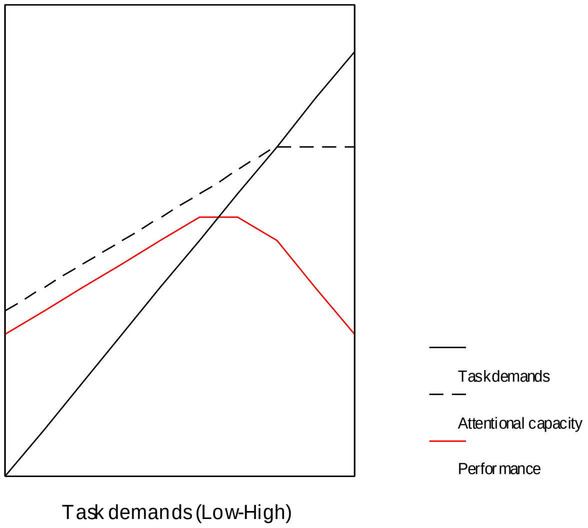


Figure 2.4 The proposed model of malleable attentional resources theory according to the correlation between task demand and performance. (adapted from Young and Stanton, 2002[b])

In summary, acceptable performance in a mental task occurs under an intermediate level of mental workload since the relationship between mental workload and performance is an inverted-U, the same as the correlation between arousal and performance (Wickens and Hollands, 2002; Young and Stanton, 2002[b]). All previous models assumed that the mental workload level could impact on an individual's attentional capacity and performance. Also, according to the MART model, low-level mental workload can lead to unacceptable responses due to a low level of arousal.

Furthermore, increasing levels of arousal can influence cognitive task performance. High-level mental workload and environmental stress can lead to an increase in physiological arousal, so performance can decline (Matthews et al., 2000). Therefore, an increase or decrease in the level of arousal can lead to poor performance, so it is important to control any factor that can increase the arousal level during task performance rather than controlling mental demands. However, there are other important factors that can place stress and strain on information processing and cognitive functions, such as physical labour, particularly while performing a job that imposes mental and physical workloads. Physical labour is the most important factor in creating a high level of arousal in an occupation that requires both mental and physical demands. Consequently, in this thesis, it is necessary to create a new model that clarifies the impact of physical workload in addition to mental demands on attentional resources. It seems necessary to consider the physical workload mechanism with attentional resource capacity in addition to mental workload.

It will be interesting to test how physical workload can work with mental underload and if there is any subsequent effect on attentional resources. As stated previously in Section 2.2, in the real domain, workload may include physical and/or cognitive components that can interact to influence operator performance. So, the following section provides theoretical background on the physical workload concept.

2.5 PHYSICAL WORKLOAD AND PERFORMANCE

A great many jobs at a great many workplaces place both physical and mental demands on the operator (DiDomenico and Nussbaum, 2008; Perry et al., 2008). Soldiers, assembly-line and manufacturing jobs all require physical effort through lifting and carrying items and mental effort which involves attention, monitoring and perception (Mozrall and Drury, 1996; Perry et al., 2008). For example, assembly jobs require, besides lifting parts and handling materials for the assembly process,, that operators must use their mental functions including perception, attention, and memory to complete the assembly tasks (Stork and Schubo, 2010). Rather than just physical exertion, some jobs may place substantial demands on workers’ mental capacity, such as emergency-room medical groups, workers in manufacturing systems, and soldiers in combat operations (Perry et al. 2008). Also, between 10%-20% of workers use their physical abilities as well as cognitive functions in their jobs in industrialised countries, regardless of the dramatically changing technological systems developments (Louhevaara and Kilbom, 2005). At the same time, dynamic work is still common in non-developed and developing countries (Louhevaara and Kilbom, 2005).

Conceptually, physical demand is a task that requires muscle work with the participation of each of these systems: musculoskeletal, cardiorespiratory and nervous (Louhevaara and Kilbom, 2005). De Zwart et al. (1995) defined physical workload as, "…all temporary short-term physical responses which can be regarded as indicators of the physical workload - changes in, for example, heart rate, breathing frequency, hormonal responses and blood pressure, but also sweating and feeling of fatigue, during work and some hours thereafter" (p.2). Physical workload in the current thesis refers to '…the demands associated with tasks that require physical work from the operators, thereby utilizing the musculoskeletal system, the cardio-respiratory system, and the nervous system of the human body' (Louhevaara and Kilbom, 2005). According to Sluiter (2006), physical demands:

> "……may refer to energetic (aerobic or anaerobic), biomechanical (static and dynamic demands on the musculoskeletal system) or environmental demands" (p.433).

Most researchers' studies have focused on the impact of operator performance (physical capacity), muscle activities, back injuries, and fatigue (Sluiter, 2006). For example,, in lifting tasks numerous studies have reported that increasing the size of an object or the number of lifts per minute lead to fatigue and back disorders (Mirka et al., 1994), so exceeding the upper level of physical capacity for each individual leads to fatigue. It has been reported that increasing the levels of physical activity increases fatigue and pressure on the hand and leg muscles, in particular. In the long term, this leads to poor performance (Mirka et al., 1994). Physical workload can affect performance by influencing the muscular activity of the operator (Laursen et al., 2002). For example, it has been reported that increasing levels of repetitively lifting boxes leads to poor performance since the fatigue of back muscles and increase in bending act on the lumbar spine (Donald and Adams, 1998).

Operator characteristics, such as age, gender, anthropometrics, functional capacity and fitness are very important factors related to physical workload (Louhevaara and Kilbom, 2005), and also it depends on the nature of the physical job, such as time of task, load lifted/carried and body posture (Garg and Saxena, 1980). Kahya (2007) noted that many researchers have studied the effects of each of these factors—gender, age, experience, and interpersonal relationships—on worker performance and their contextual response. In contrast, he claimed that no study or experiment has been dedicated to the influence of task characteristics and job conditions on operator performance and contextual response.

In particular, the tasks' demands, difficulty, and complexity, as well as type need to be taken into account. Some physically demanding jobs, such as mechanical and maintenance, need a high level of skill. He also mentioned that workplace conditions are important factors, such as surroundings (noise, lighting, humidity, dust, and temperature) and motivation. Poor conditions decrease the worker performance and lead to low quality, productivity, and safety issues. There are some external factors that affect physical workload, such as age and health (De Zwart et al., 1995). For example, most papers have reported that the age factor hinders worker performance in physically demanding jobs because workers' age has a negative impact on the balance of physical demands and physical work capacity. Thus, this aspect increases the hazards of disease for the operator.

It is necessary to balance the tasks' physical load and workers' physical functional capacity to get an acceptable performance and reduce injuries and errors (De Zwart et al., 1995). There is a strong relationship between physical workload and operator fatigue (Karlqvist et al., 2003). Indeed, a high level of physical demands can lead to many troubles, such as cardiovascular risks and musculoskeletal problems (Karlqvist et al., 2003). As this thesis concerns gender differences as an individual difference factor, it is valuable to clarify the gender differences in physical strength. Thus the next section provides a summary of differences in males and females in performing physical activities.

2.5.1 Gender Differences and Physical Activity

The significant differences between genders in physical activity have been reported in several studies. In general, there are different factors that impact on physical activity such as age, gender, and training (health). This is because there is a difference between men and women in physiological and cardiac strength (Borg, 1998). Also, there are differences in male and female body structure, such as anthropometry, muscle strength and physical capacity (Lindbeck and Kjellberg, 2001). In addition, the type of physical activity and duration are important factors that have an impact on individual physical workload capacity (Hill and Smith 1993). It has been reported that male participants are more active than females and female muscles fatigue more quickly than male (Trost et al., 2002). Furthermore, the maximum oxygen consumption (VO_2 max) increases significantly in women compared to men, when they perform a high-intensity cycling exercise (Hill and Smith, 1993). The important issue in aerobic capacity gender difference is the aerobic test mechanism. Hill and Smith (1993) reported that the differences between men and women became significant when they performed a short, highly physical cycling load exercise and this load was constant for both genders. In contrast, they reported that the gender differences disappeared when the mechanism of the physical test was expressed relative to the body mass of the individual. Therefore, most researchers have set up physical load resistance in cycle ergometer tests or on a treadmill relative to the maximum capacity workload for each participant in order to reduce the difference between individuals and genders.

Moreover, the cardiac system showed a significant difference between genders in different types of physical exercises, such as cycling or running. It has been concluded that females recorded a higher mean of physiological variables such as heart rate, blood pressure and temperature than males in submaximal physical activity (Borg, 1998), but these differences depend upon the period of physical exercise (short- or long-term period). However, other studies have mentioned that there is no significant difference in heart-rate variability between females and males in intensity exercises if the physical loads are adjusted to the body weight of participants (Perini et al., 2000). Borg (1998) stated that a difference in physical subjective assessment tools (Borg RPE scale and Borg CR10 scale) between men and women was observed in some studies. He found that women usually rate significantly higher scores than men in the same physical exercise.

Having discussed the mental and physical workload concepts and theoretical aspects, it now seems appropriate to cover and illustrate how physical actions work with the cognitive functions and relate with them. This is covered in the following section.

2.6 PHYSICAL AND MENTAL WORKLOAD INTERACTION

In this section the impact of physical workload on mental and information processing is discussed. Many researchers have focused on the separate impacts of physical and mental demands on individual performance. Mental workload has increased more than physical workload in many jobs due to the rapid increase in technology in recent years; however, there are still many jobs that require physical activities as well as mental tasks that can place stress on cognitive functions, as mentioned earlier. However, the relatively small number of authors who have studied the effects of physical activity on cognitive function have reached rather different findings (Antunes et al., 2006; Mozrall and Drury, 1996; Tomporowski and Ellis, 1986; Tomporowski, 2003). However, most studies have focused on physical workload capacity; studies on the impact of physical loads on cognitive tasks are rare (Mozrall and Drury, 1996). According to some researchers, the optimum cognitive performance occurs under a medium level of arousal that happens due to physical stress (Audiffren et al., 2008). So it would appear that the contribution of physical exertion with mental loads in task performance is significant and constitutes a gap in the literature.

In fact, there is currently a lack of understanding of the mechanisms behind and the interaction between physical activities and components of the cognitive information processing system. Some researchers (Audiffren et al., 2008; Mozrall and Drury, 1996) state that increasing levels of physical exercise lead to an increase in arousal state. Furthermore, the authors proposed three aspects that can affect information processing through physical exercise-arousal, brain activation, and effort level (Audiffren et al., 2008). Many studies have proved that an increased level of arousal due to incremental increases in physical demands significantly impacts and supports cognitive task performance (Audiffren et al., 2009). On the other hand, other researchers postulate that some levels of physical effort, such as a moderate level, can facilitate mental processes by increasing the percentage of blood flow, and thus oxygen, to the brain (Antunes et al., 2006), creating a defence against any reduction in available oxygen in the brain due to mental stress and resulting in improvements in cognitive function. Consequently, it seems that the contribution of physical workload in information processing is important, and it could be very interesting to test the mechanism of physical workload with low levels of mental workload, because this combination may facilitate performance under low-level mental workloads by increasing the level of arousal and oxygen flow to the brain. Therefore, this thesis deems it necessary to investigate this interaction.

The researchers who have studied the influence of these effects on performance reported varied findings. Some of them found that the physical and mental loads did not impact on human responses (e.g., Lemmink and Visscher 2005; Perry et al. 2008), while others found that intermediate and high levels of physical workload impeded performance (DiDomenico and Nussbaum, 2008, 2011). However, most researchers have concluded that intermediate levels of physical loads facilitate mental tasks and information processing (e.g., Brisswalter et al., 2002; Joyce et al., 2009; Reilly and Smith, 1986).

Because some researchers have suggested that optimum performance in mental tasks occurs under moderate levels of physical workload, the correlation between physical demand and performance is an inverted-U, which indicates that acceptable performance occurs under moderate levels of arousal (Audiffren et al., 2009; Brisswalter et al., 2002). In addition, physical activity has been shown to have an impact on cognitive functions (Fredericks et al. 2005). However, the type of mental task used in investigations of the impact of physical and mental workload on performance is an important factor that affects previous studies (Tomporowski, 2003). The conclusions from the studies were not uniform because they all built upon studies that employed simple mental tasks, and they did not consider the multiple resources model by Wickens (1984), which assumed that visual and auditory resources in the cognitive processing system have different information processes (verbal and spatial resources) and different capacities (Mozrall and Drury, 1996). Furthermore, the interaction of physical workload with mental underload has not previously been considered and, according to Young and Stanton's (2002^b) MART theory, as mentioned previously in Section 2.4.4, this can have a serious negative impact on mental underload in individual performance; the same is true with mental overload due to the reduction in the capacity of attentional resources to relate to low-level arousal. Researchers have focused on simple reaction-time tasks, and they tested different physical loads on one level of mental workload. Consequently, this thesis assumes that it is necessary to derive a new model from Wickens' model and to investigate the mechanism of physical workload with the attentional resource capacity of this model. In addition, it seems necessary to understand how various levels of physical workload interact with different levels of mental workload tasks. This will help provide a partial explanation for the inconsistent results in these studies. Also, it will add a valuable contribution to the ergonomics literature on how physical and mental workloads interact in multitask situations. Table 2.1 summarises some selected studies to illustrate the variations in the results of the effects of physical activities on cognitive tasks.

In general, the optimum mental task performance occurs at an intermediate level of arousal, the same as the relation between mental workload and performance as stated previously in section 2.4.4. The major aim of the current project was to evaluate individual performance under a dual-task paradigm (physical and mental demands). Various tasks in the real world require both workloads, particularly in industrial fields such as manufacturing and assembly (Mozrall and Drury, 1996). However, some researchers have found that physical workload has no impact on various mental tasks. For example, Perry et al. (2008) examined the impact of standing, walking and jogging on visual loading simulation tasks, and they concluded there was no significant impact on time and percentage of errors made. They said that the impact of physical efforts on this task were not clear, maybe because the mental task used in this experiment is highly complicated and not suitable for causing performance to be responsive to physical demand.

Other authors have found that there was no influence on visual and auditory choice reaction time tasks during a medium and high-intensity running activity (Lemmink and Visscher, 2005). These results are consistent with other studies that reported no significant influence on decision-making in soccer tasks during different levels of exercise (cycling at 0%, 70%, 100% of maximum workload capacity) (McMorris and Graydon, 1996) and simple, visual and complex reaction time tasks (Allard et al., 1989).

A unique study of 30 participants (aged 18-24 years) in the United States investigated the effect of different levels of physical lifting tasks (0%, 8%, 14%, and 20% of body weight) on different levels of auditory arithmetic tasks. They concluded that increasing levels of physical workload did not have a significant impact on the accuracy of mental tasks (Astin and Nussbaum, 2002; DiDomenico and Nussbaum, 2008). In contrast, Bender and McGlynn (1976) studied the impact of different levels of treadmills (0%, 40%, 50%, 70%, and 95% of mean HRmax in 3 min duration) on a visually simple reaction time, and found that increasing levels of physical exercise impaired performance. However, DiDomenico and Nussbaum (2011) stated that the mental arithmetic task performance was impacted by the type of physical effort (i.e. elbow flexible, knee extension and whole-body carry) and frequency of movements (i.e. low and high) whereas, they founded that the effect of force exertion level (i.e. low, medium and high) on arithmetic task is not significant.

An important study of 10 male participants by Reilly and Smith (1986) was conducted to examine the effects of different physical demands (0%, 25%, 40%, 55%, 70%, and 85% of VO_2 max) on a pursuit rotor task. They found that the performance of subjects was reduced at the low and high levels of physical load, and optimum performance occurred at the middle level (38% VO_2 max). This result supports the assumption that the correlation between physical activities and mental tasks is an inverted U-shape due to the incremental increases in the arousal level which, which in turn increases attentional capacity and supports cognitive information process. Since, the relationship between arousal level and cognitive task performance is U-inverted (Audiffren et al., 2009). Also, Arcelin et al. (1998), dealt with the relationship between moderate-intensity physical workload on cognitive task performance, especially on information processing. In this experiment, the subjects completed 10 minutes of physical exercise at 60% of maximum work capacity on an ergometer bicycle and two levels of visual Choice Reaction Time (CRT). Generally, they observed that the moderate intensity physical activity had an impact on speeding up information processing such that the speed of responses by the subjects increased with the physical activity (Audiffren et al., 2009; Brisswalter and Delignieres, 1995; McMorris and Graydon, 1996; Pass and Adam, 1991).

A study by Audiffren et al. (2008) showed the impact of 90% of VO_2 maximum on two levels of auditory intensity reaction time tasks (45 dB, high and 80 dB, low). They found that the exercise improved reaction times on both auditory levels. They said the physical activity had reduced the reaction time to a low auditory level rather than a high level. Furthermore, Joyce et al. (2009) found that the 40% maximum aerobic workload (medium level) facilitated the time and accuracy of participants during Stop-Signal Reaction Time (SSRT) tasks. Also, it has been reported that a moderate level of exercise (50% of maximal workload capacity (MWC)) facilitated the means of a visual reaction time better than 20% workload capacity, since the researchers said that the reaction time during 50% of MWC was faster than at rest level (Joyce et al., 2009).

Table 2.1 The effects of physical workload on cognitive tasks performance

Study	Subjects	Physical activity	Mental task	Results
Audiffren et al, (2008)	n=28	Bicycle pedaling 90% maximum VO2, 8,14,22,28, 34 and 40 min	Auditory of signal RT (2 levels)	Facilitated accuracy and time at moderate level(28 and 34 min)
Arcelin et al, (1998)	n=22	Ergometer bicycle (low, 60% of maximal workload capacity and high, 10 min)	Visual CRT	Moderate level of exercise (60%) supported reaction time and error rate
Davranche and Audiffren, (2004)	n=16	Ergometer bicycle (20 and 50 % of maximum workload capacity , 6 min)	Visual CRT	Moderate level (50%) supported reaction time and accuracy
DiDomenico and Nussbaum (2008)	n=30	Lifting boxes (0%, 8, 14 and 20% of body weight, 5 min)	Auditory mathematical problems (three levels)	No effect
Joyce et al (2009)	n=10	Ergometer bicycle (40% maximum workload capacity, 4 min)	Stop-signal RT task	Moderate level facilitated accuracy and time
Lemmink and Visscher, (2005)	n=16	Ergometer bicycle (low intensity at 75W and high intensity)	MCRT of (Visual and auditory) of soccer players	No impact accuracy and time
Pass and Adam, (1991)	n=16	Ergometer bicycle (low, 60% of maximal workload capacity and high, 40 min)	Visual perception task	Facilitated
Perry et al, (2008)	n=16	Treadmill (stood, walked and lightly jogged, 10 min)	Visual helicopter loading task (planning task)	No impact on accuracy and loading rate
Reilly and Smith (1986)	n=10	Ergometer bicycle (25, 40, 55, 70 and 85% of maximum workload capacity , 6 min)	Psychomotor task and arithmetic task	Moderate level of exercise (44-55%) supported performance
Yagi et al. (1999)	n=24	Ergometer bicycle (rest, at 130-150 HR level and recovery, 5 min)	Visual and auditory P300 RT tasks	Exercise facilitated both tasks but visual facilitated greater than auditory

Yagi et al. (1999) found that the accuracy and reaction times of participants in visual and auditory P300 under a pedalling condition (physical level between 130-150 b/min of HR) are better than during rest and recovery conditions. They reported that moderate physical activity can support performance by assessing the participants' quick shift to allocate attention from a visual task to an auditory task, and the visual task was supported more strongly than the auditory task, which may be because the auditory function needs more information processing time to recall stored data.

In some experimental studies, researchers have suggested that physical workload can facilitate task completion time but not accuracy. For example, the decision-making time of football players in a decision-making test was improved by physical activity but their accuracy was not (McMorris et al., 1999). In these studies, the authors have assumed that the relationship between mental tasks and performance is curvilinear, based on the arousal model (Mozrall and Drury, 1996). Therefore, the incremental increase in the arousal state is due to increasing levels of physical activities, leading to optimum cognitive performance.

The variations in all previous results can be explained through several aspects that are related to physical workload and cognitive demands.

- ✓ In physical exercise, the time duration of tests and the physical intensity aspects, for example, the impact of long-duration exercises (e.g., 50 minutes or more) on cognitive tasks, differ from the results of short-duration anaerobic exercises (between 30 seconds and 30 minutes). Since different authors have studied the effects for different periods of time, this may affect their results (Tomporowski and Ellis, 1986). DiDomenico and Nussbaum (2011) examined different physical activities (i.e., physical efforts, frequency of movements, and force exertion levels) on cognitive information process and found that the physical effort and frequency of movement significantly affected arithmetic performance, but the force exertion level (i.e., physical lifting workload) did not.
- ✓ In cognitive tasks, there are two types of tasks (visual or auditory) and mental tasks of varying duration (Mozrall and Drury, 1996).

Indeed, there are significant limitations in previous studies. The major limitation has been that the authors have considered the attentional resources of participants as a single visual or auditory resource (Mozrall and Drury, 1996; Yagi et al., 1999). In other words, they did not take into account the assumption of the multiple attentional resources model (Wickens, 1984), which proposes that attentional resources include a number of dimensions of resources and each resource has various capacity limits. In particular, researchers have disregarded the verbal and spatial codes in this model as resources different from the visual and auditory senses. As mentioned in section 2.4.4, the assumption proposed by MART (Young and Stanton, 2002[c]) shows that the shrinkage in attentional resource capacity due to mental underload could lead to performance failure based on the inverted-U relationship between arousal and performance.

These previous studies did not consider the effects of mental workload with physical load effects on visual and auditory resources. The studies focused on simple mental tasks such as reaction time and choice of reaction time tasks (Joyce et al., 2009; Yagi et al., 1999). These simple tasks do not adequately reflect the impact of physical workloads on complex cognitive tasks (Dietrich et al. 2004). Moreover, most of these studies examined the impact of physical exercise on cognitive tasks after exercise sessions (not simultaneously with exercise) to evaluate fatigue effects (Tomporowski 2003). Therefore, it seems from this appraisal that the impact of different levels of physical workloads on cognitive task performance is too important to offset these limitations and support the ergonomics literature on this issue.

2.6.1 Mental and Physical Workload Against Gender Differences

Most studies have focused on the gender difference between either cognitive tasks or physical activity, separately. Studies that examine the differences between men and women during mental and physical tasks concurrently are limited (Silbley and Beilock, 2007; Yagi et al., 1999).

It has been stated that the differences found between genders within the mental and physical domains depend on the type and difficulty level of the physical and/or mental task, and the duration of the task (Yagi et al., 1999). Yagi et al. (1999) reported that the differences between males and females in accuracy and time of task are not significant in auditory reactions to task interactions with aerobic activity. They argued that there was no gender difference in accuracy and time of correct responses while performing visual reaction time tasks and cycling tasks concurrently. They said that because performance was facilitated by physical exercise, the differences decreased. In contrast, a gender difference has been observed in heart-rate since the average heart rate is higher in females than males in both types of tasks (auditory and visual). This may be due to the difference between genders in cardiac capacity. Furthermore, results have shown that the physical activity facilitated the visual task more than the auditory task. Also, researchers have mentioned that the gender differences may disappear because the mental tasks that are used in the study are simple (reaction time) and they used one level of workload interaction.

The determination of gender differences with mental and physical tasks simultaneously in previous studies is very limited. Therefore, it is worthwhile examining the gender differences between males and females under different levels of physical and mental workloads in order to determine if there are any significant differences between them under more complex work systems.

2.7 WORKLOAD MEASUREMENTS

There are various methods of assessing mental workload, because MWL is a multidimensional concept that relates to different aspects, such as mental effort, time pressure, and stress (Reid and Nygren, 1988). The technique to measure mental workload should include four features (Megaw, 2005): sensitivity, diagnosticity, intrusiveness and validity (p.525). However, mental workload measurement techniques can be categorised into objective and subjective measurements. Performance (such as time of correct responses, number of correct responses, and reaction times) and physiological parameters (heart rate and heart rate variability) are defined as objective measures.

2.7.1 Mental Workload Measurements

2.7.1.1 Performance Measures

These measures depend on the primary task assessment and/or a secondary task. These techniques are commonly used to assess a mental workload’s difficulty. Many researchers have used this measure in different studies, and they have proved that the responses are sensitive to mental demand changes under specific circumstances (Megaw, 2005; Lee, 2001). The primary task can be measured by recording different variables, such as number of correct responses, time of responses and accuracy. For example, Lee has measured the effect of mental workload of a tone localisation task on individual performance, by measuring the number of correct responses when this was the primary task, and he found that increasing the number of sound sources (speakers) decreased the number of correct responses. He therefore concluded that the performance measure is sensitive to mental demand changes (2001).

According to Megaw (2005), the limitations of primary tasks are first, that optimum performance does not necessarily reflect the optimum task workload, since according to the attentional resources model, the task workload can be within the range of attentional resource limits. Second, these kinds of measures cannot reflect an accurate amount of task workload over a short time for mental tasks. However, this method is usually still used and it has been reported that although such performance measures may be sensitive to mental load variation, that related to task loads, individual differences and resources determine the allocation strategy (Cegarra and Chevalier, 2007).

The aim in using a secondary task technique is to evaluate the residual capacity that is not used in performing a task. This technique has been used in experimental studies with concurrent tasks (Wickens, 2008). It has also been used to reflect the impact of mental workload level changes on primary tasks in different types of task conditions, such as driving and monitoring tasks (e.g., Hwang et al., 2008), in particular, the influence of mental underload on the main task (e.g. Young and Stanton, 2002). For example, Hwang et al. (2008) found that increasing the level of difficulty in the primary task (monitoring in a control room) led to performance decrements in the secondary task (an arithmetic task). The researchers reported that the changes in mental effort significantly impacted the secondary task responses. However, the secondary task method is appropriate for short-duration mental tasks and more suitable for the investigation of automation on performance (Young and Stanton, 2004).

However, most previous research has used performance measures widely as an indicator to reflect the impact of physical demands on cognitive tasks (Tomporowski and Ellis, 1986; Tomporowski, 2003) and it has been reported that performance measures such as correct responses and speed of correct responses are sensitive to increasing levels of physical workload. For instance, DiDomenico and Nussbaum (2008) showed a significant decrease in participant accuracy when the overall workload increased. Furthermore, it has been reported that the reaction time increased significantly as physical and mental demands increased (Tomporowski, 2003). However, some researchers have reported that the reaction time improved under moderate physical loads (Reilly and Smith, 1986). Thus, the current research used this measure to assess the effect of overall workload on individual performance.

2.7.1.2 Physiological Parameters

Different physiological measures reflect the impact of mental workload on performance. These measurements reflect the changes in cardiovascular systems due to cognitive stress and refer to physiological arousal states induced by mental effort. Many physiological indices are reliably sensitive to cognitive workload (Young and Stanton, 2004). The most common physiological variables used to evaluate mental workload are listed below.

Heart Rate (HR) and Heart Rate Variability (HRV)

Heart rate and heart rate variability are widely applicable physiological measurements and are sensitive to mental workload changes. The impact of physical and mental workloads on the cardiovascular system can be reflected by changes in HR and HRV. Sympathetic and parasympathetic actions of the nervous system can have an impact on heart rate and heart rate variability, so considerable HR and HRV alterations occur as mental activity increases. HR has shown significant sensitivity to mental demand changes in different environments, such as pilots’ tasks (e.g. flight control; Hankins and Wilson, 1998), visual monitoring tasks (primary tasks) and arithmetic problems (secondary tasks; Hwang et al., 2008). Furthermore, HRV is sensitive to mental demand changes, in particular, of complex mental tasks. HRV refers to the beat-to-beat variation in heart rate. HRV was originally assessed by calculating the mean beat-to-beat heart rate commonly called the RR interval. HRV is an indicator of the interaction between cardiac sympathetic and parasympathetic activities that cause changes in the beat-to-beat intervals. Short-term differences in the beat-to-beat interval are reduced by reduced parasympathetic activity or sympathetic actions. HRV is related to a highly increased level of heart rate induced by a high level of physical exercise (Sammer, 1998).

Increasing levels of mental effort have reportedly led to increased/decreased heart rates (Middleton et al., 1999; Veltman and Gaillard, 1996). Continuous recordings of heart rates and heart rate variability are sensitive to mental workload difficulties. HR showed significant differences from baseline values while mental (visual) activity increased and heart rate variability decreased (DiDomenico and Nussbaum, 2011; Hwang et al., 2008). HRV findings are significantly influenced by different attention tasks, such as flight tasks and a ship navigation simulator (Gould et al., 2009; Veltman and Gaillard, 1996). The responses of these measures vary from task to task, and HRV is recommended for use as a more sensitive metric than HR, to reflect the change of mental loads in complex cognitive tasks (Hansen et al., 2003; Veltman and Gaillard, 1998). The most advantageous aspect of heart rate and heart rate variability is the ease and simplicity in recording while performing the task. HR has been shown to be sensitive to other environmental factors, such as physical load, noise and temperature, as well as mental demands (Hansen et al., 2003). These physiological measures should be sensitive to any type of cognitive task as difficulty levels change. It has been reported that there is a correlation between an increase in cognitive demands and an increase in mean HR, whereas HRV decreased significantly as mental effort increased (Veltman and Gaillard, 1996). Therefore, both HR and HRV are sensitive and valid to assess changes in mental workload. In addition, Hwang et al.(2008) said that HR and HRV have been shown to be valuable indicators of mental workload, since they showed a highly significant correlation between these variables and mental workload changes. Furthermore, both measures are used to reflect changes in physiological arousal while performing mental tasks (Hansen et al., 2003).

Blood Pressure (BP)

Most recent research has used a blood pressure measure to estimate the mental workload level in different situations (Hwang et al., 2008). The blood pressure measure has been demonstrated to be influenced by different mental tasks (Hwang et al., 2008; Veltman and Gaillard, 1996). BP is more sensitive to physical demands than to mental workload (Fredericks et al., 2005). However, BP refers to the pressure in blood vessels (arteries) that transport blood from the heart during cardiac contractions. BP includes minimum blood pressure (i.e., diastolic pressure), which occurs when the blood pressure becomes low inside the arteries during a resting state of the heart muscle. In contrast, high blood pressure (systolic pressure) occurs during the contraction of the left ventricle of the heart (Kroemer et al., 1997). Hwang et al (2008) found that there is a significant correlation between increasing levels of mental workload and increasing levels of systolic blood pressure, as there is in heart rate. Therefore, it seems that this measure is valid, and is suitable to use to assess mental workload. Also, the effect of workload on the cardiovascular system and physiological arousal can be indicated by BP changes (Fredericks et al., 2005). Generally, BP changes during mental effort are related to HR changes, especially in the short term (Fredericks et al., 2005; Veltman and Gaillard, 1996). BP sensitivity to tasks includes different sub-tasks, such as pilot tasks. For example, it has been concluded that there is a significant difference between the BP value while performing a flight task and a rest level (Veltman and Gaillard, 1996).

Eye Blink Activity

A suitable measure that can be used as an indicator of visual information processing workload is eye blink frequency. This measure can be found by measuring blink frequency and duration parameters. This measure has been used widely in different studies, such as flight tasks (Hankins and Wilson, 1998; Wilson, 2002) and visual tasks involving coloured words (Iwanaga et al., 2000) and visual monitoring (Hwang et al., 2008). According to these authors, the blink frequency decreases as the complexity of mental demand increases and, at the same time, blink duration becomes shorter at a higher level. However, in some cases, because of a tendency to blink after receiving visual information, the blink rate becomes greater under a high mental workload, so the correlation between eye-blink rate and mental demand is not always negative (Megaw, 2005). However, this measure has been used to reflect an increase in the level of physiological arousal during mental demands, but is not sensitive to physical workload alterations.

2.7.1.3 Subjective Assessment Tools

Subjective assessment tools are important in evaluating mental workload because these techniques provide valuable information on perceived mental workload demands. A number of subjective techniques have been developed. The advantage of these tools is that they are easy to use in the field. The data support the fact that these tools are sensitive to any variations in cognitive tasks in both single- and dual-task conditions (Rubio et al., 2004). The scores are sensitive to changes in effort under constant levels of primary task performance (Young and Stanton, 2004). Generally, these subjective tools can be divided into unidimensional and multidimensional scores. These techniques depend on the feeling and perception of the participants towards the level of task demands. The most common unidimensional ratings are the Cooper-Harper Scale (CHS), while the NASA Task Load Index (NASA-TLX) and Subjective Workload Assessment Technique (SWAT) are two common multidimensional tools.

Cooper-Harper Scale (CHS)

This scale was created to evaluate pilot-handling task demands. It has been used widely as a unidimensional rating scale in many studies within the aviation domain. This tool reflects the aircraft's handling characteristics (Megaw, 2005). The Cooper-Harper scale is suitable for assessing a combination of handling difficulty of the aircraft and the mental demands of flying. The Cooper-Harper scale can be considered as an interaction between the mental workload with the handling qualities (Wierwille and Casali, 1983). The score is sensitive to psychomotor tasks, in particular, aircraft handling qualities. There is no verbal explanation in this score that refers to the workload. The scale depends on a decision tree that includes the pilot rating points from 1 to 10. In this scale, "1" means very easy to select and do the required task, whereas "10" means very difficult to deal with the aircraft system's display.

This scale has been developed into a Modified Cooper-Harper Scale (MCS) (Wierwille and Casali, 1983) in order to make it suitable for mental tasks other than flight control. It has been assessed in several studies, such as solving mathematical tasks during simulator flight tasks and whether perception of the aircraft engine device decreases during the main flight simulator task (Casali and Wierwille, 1984). Therefore, these findings confirm that MCS is valid and reliable for measuring overall mental workload.

Subjective Workload Assessment Techniques (SWAT)

SWAT is considered a multidimensional assessment tool to measure mental workload. The key feature of this tool is based on participants' assumptions of how they can improve their mental task performance. Numerous researchers have used SWAT as a psychological model in order to evaluate cognitive information processes. SWAT includes three-dimensional measures: time load, mental effort load, and psychological stress load. Each of these loads contains three levels of demand: low mental level (1), medium level (2), and high level (3). These loads produce 27 combinations of workload. Table 2.2 presents an explanation of the SWAT score dimensions and levels.

In the SWAT scale, measurements are needed to complete a sorting card (SC) task before starting the main task. It is time-consuming, especially for complex cognitive tasks (Reid and Nygren, 1988). Participants need to arrange cards according to the levels of mental demand, and each card represents a combination of three levels. They need to start with the card that reflects a simple mental load (1-1-1) and finish the sorting task with a card that signifies a difficult mental load (3-3-3). At the beginning, the individuals are required to assign weightings to the scale's dimensions regarding the importance of each dimension in the task as a conjoint measurement procedure (Reid and Nygren, 1988). SWAT has been used intensively in different types of experiments and has shown sensitivity to mental changes in workload levels (Rubio et al., 2004). However, the score is not suitable for evaluating very low mental demands (Hart and Staveland, 1988). Luximon et al. (2001) said that, according to previous studies, researchers have concluded that the NASA-TLX rating is more advantageous than the SWAT score in measuring a low mental level. SWAT has been used to capture variations in mental workload in laboratory experiments in different ways—single-task and multitask demands.

Table 2.2 The SWAT scale dimensions and definitions (reproduced from, Megaw, 2005, p.543)

Time Load	Mental Effort Load	Psychological Stress Load
1. Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.	**1.** Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.	**1.** Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.
2. Occasionally have spare time. Interruptions or overlap among activities occur frequently.	**2.** Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention required.	**2.** Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.
3. Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time.	**3.** Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.	**3.** High to very intense stress due to confusion, frustration, or anxiety. High to extreme determination and self-control required.

NASA-TLX (Task Load Index)

This is the most common subjective MWL scale used in experimental studies. It is multidimensional and easy to administer compared to other scales. This scale was developed by Hart and Staveland (1988) after extensive research. The TLX has been supported by many studies in laboratory conditions and it has shown the significant impact of workload changes (Hart and Staveland, 1988). The TLX evaluates overall workload and depends on the weighted average rating of six dimensions or sub-scales: mental demands (MD), physical demands (PD), temporal demands (TD), own performance (OP), effort (EF), and frustration (FR) (Hart and Staveland, 1988). Each dimension range is shown from 0 to 100. Table 2.3 illustrates the TLX scale dimensions and the definitions.

The most valuable features of this scale compare well with other rating scales (e.g., SWAT) as the physical sub-scale refers to the difficulty of physical activity in tasks. It has also been shown that the TLX score is applicable for assessing workload in physical and mental interaction conditions (i.e. concurrent tasks) (Astin and Nussbaum, 2002; DiDomenico and Nussbaum, 2008; Fredericks et al., 2005; Perry et al., 2008). These studies have concluded that increasing levels of mental and physical workloads lead to higher TLX scores.

One significance aspect of the NASA-TLX is in the physical subscale, making this scale multidimensional and suitable to assess overall workload in tasks that require concurrent physical and mental workload. Most authors use this scale to evaluate mental workload and some have disregarded the physical workload factor on individual performance (Hart, 2006). In addition, the implication of the physical dimension in this scale concerns the impact of physical effort on overall individual workload and performance. The validity of this has been confirmed by Hart and Staveland (1988), who found a significant correlation (0.52) between the overall workload and physical effort subscale; the same result is seen between mental effort and overall workload (0.73). The physical dimension can affect participants' feelings toward the level of mental demand, since the effects of physical workload on information processing have been shown, and some researchers have postulated that an intermediate physical workload could improve mental information processing by supporting performance (Audifferen et al., 2008). In addition, improvements in mental performance due to physical workload could change the feeling of participants in scoring the effort and temporal demand subscales, by reducing the rating of the overall workload score. Therefore, this research assumes that the physical workload subscale as one dimension in the TLX is important and can reduce the overall workload score and difficulty through the improvements that occur under a moderate level of physical demand. For example, as mentioned previously, Reilly and Smith (1986) concluded that a medium level of physical exercise supports and improves the time of correct responses and accuracy in cognitive tasks. Therefore, it seems that the importance of the NASA-TLX appears in the physical demand subscale, since it can show how physical workload contributes to mental performance from the participants' perspective, so the present research has used this scale to evaluate the overall workload of both physical and mental workload interactions.

Table 2.3 NASA-TLX dimensions and definitions

Dimensions	Endpoints	Description
Mental demand	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical demand	Low/High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal demand	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Performance	Low/High	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration	Low/High	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

There are two protocols to calculate the overall score of sub-scales: weighted and unweighted protocols. Numerous studies have illustrated that the relationships between weighted and unweighted scores are strong (Cao et al., 2009). This is consistent with DiDomenico and Nussbaum (2008), who found that there is no significant difference between weighted and unweighted NASA-TLX scores while measuring physical and mental workloads (auditory, arithmetic, and lifting tasks). The TLX has been used to determine gender differences in mental workloads for different type of tasks (Dittmar et al., 1993). They reported that men usually have a lower overall TLX score than women.

The validity and reliability of the TLX have been supported by numerous experimental results (Hart and Staveland, 1988). The scale is sensitive to changes in overall mental workload changes from low, to medium, and high levels, and it has been used in several studies in single- and dual-task environments (Hart, 2006; Rubio et al., 2004). It is supported by many studies that evaluate workload demands, such as flight tasks (e.g., Moroney et al., 1992), driving simulator tasks, in automation conditions (e.g., Stanton and Young, 1997), and monitoring visual tasks (Hwang et al., 2008).

The implication of using the NASA-TLX in different environments, such as flight and driving (Hart, 2006) and dual tasks of physical and mental demands (DiDomenico and Nussbaum, 2008), indicates the validity of this tool in approaching a mental workload multitasking scenario. It has been mentioned that the NASA-TLX significantly correlates with other measures of mental workload (Cao et al., 2009). The TLX is better than other subjective assessments, such as SWAT and the Cooper–Harper scale, in many of this investigation’s experiments. For example, it has been reported that high scores of overall workload are associated with increasing levels of visual monitoring tasks (Hwang et al., 2008). The scale has been used to measure MWL under different conditions such as the evaluation of mental demands in vigilance tasks of long duration (e.g.,Warm et al., 2008). Finally, in repeated measurement studies, the TLX score has presented a highly reliable correlation, 0.77 (Cao et al., 2009).

2.7.2 Physical Workload Measurements

The next section covers the various measures and techniques that are used to evaluate physical workload. These measurements evaluate the amount of physical effort needed to complete a task and the changes of physical workload through task performance (Louhevaara and Kilbom, 2005). Performance aside, there are two main types of techniques that have been devised to evaluate physical workload while performing a task: physiological measures and subjective measures. The details of these types of measurements are explained in the following sections.

2.7.2.1 Physiological Measures

Physiological measures are generally used to evaluate the maximum physical capacity for the individual while performing a physical task. The major aims are to use these measures to assess the level of physiological arousal induced by physical activities and assess the cardio-respiratory (aerobic) capacity (Louhevaara and Kilbom, 2005). There are a number of physiological variables that reflect the impact of physical demands on physical capacity or physiological state: oxygen consumption (VO_2), heart rate (HR), blood pressure (BP), ventilation, body temperature, electromyogram (EMG), muscle strength, speech analysis (Fredrickers et al., 2005) and heart rate variability (HRV) (Rennie et al., 2003; Sammer, 1998). The following sections describe the most common of these measures.

Oxygen Consumption (VO_2)

Oxygen uptake (VO_2) is the amount of oxygen that is consumed while performing dynamic work; in other words, the quantity of air consumed per time unit. This measure refers to the energy expenditure of an individual body due to physical work. VO_2 is considered a valuable indicator to reflect the physical loads of tasks and the environmental factors that influence physical capacity (Louhevaara et al., 1985). It provides worthwhile information about the aerobic component in a lengthy period of physical activity. (Aminoff et al., 1998). The important aims of VO_2 are to identify the levels of physical workload of different types of jobs from small dynamic workload tasks to heavy ones such as slow walking, manual materials handling, and pedalling with a resistance of less than 150 Watts (Louhevaara and Kilbom, 2005). VO_2 has been used in several studies to identify the maximum workload capacity of individuals (Mital and Govindaraju, 1999).

This measure has been used widely to assess the physical workload difficulty in several types of experimental studies. The reliability of this measure has been confirmed as a good indicator of physical workload capacity (Kroemer et al., 1997). Borg (1998) has shown that there is a linear relationship between VO_2, heart rate and systolic blood pressure, since all these variables significantly increased as the level of pedalling resistance increased from 150 Watts to 200 Watts. Most researchers have used oxygen consumption to reflect exertion of tasks, physical loads, and physical capacity. It has been reported that there is a linear relationship between increasing percentage of VO_2 and increasing levels of cycling resistance (Borg, 1998; Hansen et al., 1988). Also, it has been widely used to determine the maximum workload capacity (Wmax) for individuals (Borg, 1998; Louhevaara and Kilbom, 2005). According to Nindl et al. (1998), the percentage of air exhaled increased as the intensity of lifting box loads increased. Furthermore, it has been shown that the metabolic energy expenditure of muscles increases during physical workload changes (Astrand et al., 2003).

There are two main protocols to identify individual physical load capacity: the cycle ergometer test and the treadmill test (Borg, 1998; Louhevaara and Kilbom, 2005). In both protocols, there are two main measures used as indicators to reflect the maximum physical workload capacity: VO_2 max and maximum heart rate (HR). Maximal oxygen consumption (VO_2 max) has been commonly used in several studies to determine the maximum physical workload capacity for individuals (e.g. Arcelin et al., 1998; Reilly and Smith, 1986).

Heart Rate (HR)

Heart rate has been widely used in different studies to reflect changes in physical workload, as it has for changes in mental demands. HR has been shown to be significantly sensitive to alterations in physical workload. There is a correlation between HR and oxygen consumption. Heart rate reflects the stress on the cardiovascular system and muscle strength due to the intensity of levels of physical activity (Kroemer et al., 1997). The main features of this measure are to continuously monitor the changes in physiology of an individual during tasks. In heart rate measures, environmental factors (e.g. noise and temperature) and personal factors (e.g. stress and anxiety) should be considered since these factors can impact on HR (Wickens and Hollands, 2000). However, HR has been used widely as a primary measure in different experimental studies in order to reflect the influence of physical workload on physiological arousal (Borg, 1990; Sammer, 1998). HR has shown a significant increase when the levels of physical demand increased on a bicycle ergometer (Spurr et al., 1988). Heart rate is often recorded to reflect an individual's physiological reaction to physical workload.

Heart rate has been used to assess the impact of manual materials handling and lifting tasks (Ciriello et al., 1990). Heart rate is significantly influenced by these factors: box size, lift frequency and height of lifts (Ciriello and Snook, 1978). Other studies have shown that continuously recorded HR showed a significant increase as the weight of boxes increased in vertical lifting tasks (Hattori et al., 2000). Furthermore, in numerous studies, heart rate has been recorded with oxygen consumption to determine the maximum acceptable weight of lifting (Mital, 1984).

Disregarding the limitations, the most important feature in heart rate measures is the joint measurement of physical and mental workload interactions. Numerous experimental studies have used HR to evaluate the impact of physical and mental tasks in various situations. Fredrickers et al. (2005) showed a significant influence on heart rate of pedalling and Stroop Incongruent Colour-Word Test combinations. Also, it has been concluded that the increase in mean HR associated with increasing levels of speed on a treadmill interacts with performance on a line-matching task (McGlynn et al., 1979). In addition, it has been reported that heart rate is sensitive to changes in levels of physical and mental auditory and visual workloads (e.g., Audiffren et al., 2008; Yagi et al., 1999).

Many researchers have used the heart rate measure alongside the perceived exertion rating score (Borg, 1990 and Borg, 1998). Continuous HR recording through physical activities has shown more sensitivity to physical difficulty levels than the perceived rating score. However, a significant correlation between HR and physical rating scores has been found. The concurrent recording of HR and rating score on a bicycle ergometer for several minutes of physical activity for different workload levels, ranging from 0.50 to 0.70 for 150 and 200 Watts, have shown a significant increase in both values of HR and rating score (Borg, 1998). Finally, this measure is commonly used to assess physiological arousal and cardiac stress due to physical workload and mental demands (Fredrickers et al., 2005), as mentioned previously in section 2.7.1. Therefore, the current research used this measure to evaluate the effect of physical and workload interactions on physiological arousal state.

Heart Rate Variability (HRV)

HRV is sensitive to increasing levels of physical exercise and it increases significantly as physical workload increases (Gregoire et al., 1999; Sammer, 1998). Furthermore, HRV increases in the recovery period after physical activity (Perini and Veicsteinas, 2003). In the frequency domain, measures of HRV indicate that low-frequency power improved with greater participation in high-intensity exercise (Sammer, 1998), which is the same as for athletes/participants (Dixon et al., 1992). Moreover, low-frequency power linearly increases with increasing levels of moderate physical exercise (Sammer, 1998). This may be because the total activity affecting energy expenditure and body weight are more important contributing factors in increasing HRV (Sammer, 1998). Therefore, HRV is sensitive to physical workload changes. Also, HRV is as accurate an indicator of intensive physical workload (Sammer, 1998) as it is of complex mental demands, and it changes frequently and responds quickly to changes in participants’ physical efforts (DiDomenico and Nussbaum, 2011; Sammer, 1998). A high linear correlation has been found between HR and HRV associated with increasing physical workload (Gregoire et al., 1996), so this is a valid measure to reflect physical workload changes and mental demand alterations, as mentioned in section 2.7.1. Thus, this thesis used the HRV measure to reflect the effect of physical and mental workload on physiological state and, in particular, to show the differences at high levels of workload interactions.

Blood Pressure (BP)

Blood pressure is one of the physiological variables and is sensitive to the cardiovascular system due to stressors such as mental workload, physical workload, and environmental factors (e.g. noise). Researchers have proven that there is a relation between oxygen consumption that occurs due to physical workload, and systolic blood pressure (Mital and Govindarajue, 1999). Blood pressure has been used to reflect the level of physical exercise in numerous experiments on bicycle ergometers and treadmills (Borg, 1998) as well as in different industrial tasks. It has been reported that increasing levels of physical exercise lead to high systolic and diastolic blood pressure (Borg, 1987). Furthermore, it has been used to reflect the load on a cardiac system due to lifting tasks with different loads. Increasing levels of lifting loads lead to increased levels of blood pressure (Asfour et al., 1986).

Borg (1998) identified ratings of perceived physical exertion in different types of physiques using blood pressure measures. Furthermore, Borg found a high correlation between systolic blood pressure and the rating score of the CR10 scale (0.79) and he said that both blood pressure and the CR10 rating scale increased significantly with increased levels of physical workload (on a bicycle ergometer). This indicates that physical loads and cognitive demands have an impact on the cardiovascular system and this has been proved by Fredericks et al. (2005). They found that the difficulties of mental tasks and high pedalling levels are associated with high systolic blood pressure. Therefore, blood pressure seems a suitable measure to reflect changes in physiological stress and the cardiovascular system due to changes in physical and mental workload interaction (see section 2.7.1) and so, in this thesis this measure was used to evaluate the overall workload for this purpose.

2.7.2.2 Subjective Assessments Tools

There are a number of scales that have been produced to evaluate physical workload levels. These ratings have been developed to reflect the physiological impact and pain perceived due to physical activities (Borg, 1990). These scales can reflect participants' feelings toward the level of physical intensity. Subjective ratings are essential complements to behavioural and physiological measurements of physical performance and work capacity. This is true for both theoretical analyses and applications. The two most common scales that have been used widely in different studies to reflect physical exercise intensity and capacity are the Borg-RPE and Borg-CR10 scales. However, other methods can be used to assess physical demands, such as pain estimation charts, visual analogue scales (VAS) (Borg, 1998), and several variations of methods for determining maximum acceptable weights (Garg and Saxena, 1980).

Borg's RPE and Borg's CR10 Scales

The rating of perceived exertion (RPE) has been developed to evaluate the difficulty of processing physical loads. This scale includes a significant feature of comparing scales that use verbal anchors to identify the physical level (Borg, 1998). Furthermore, the RPE scale can evaluate physiological variables. The process of using this scale depends on an assumption that increased physiological stress is associated with physical exercise level (Borg, 1982). Thus, individual perception of physical load is increased. Numerous experimental studies have shown that in increasing levels of physical exercise, VO_2 and HR led to increasing RPE scores (Borg, 1982 and 1998). The scale's ratings range from 6 "no exertion at all" to 20 "maximal exertion" as shown in Figure 2.5.

The RPE scale has been used in several studies to assess physical workload, back pain, and physiological stress such as on a bicycle ergometer (Kamijo et al,, 2004; Reilly and Smith 1986), a treadmill (Borg, 1998), manual handling tasks (Li et al., 2009), and lifting loads (Hattori et al., 2000). All these studies have shown significantly increasing RPE scores as physical workload increased. Furthermore, the RPE has successfully reflected the difficulties of physical loads in lifting tasks in line with increases in weight, size, and lifting distance (Hattori et al., 2000). The RPE scale was created from the information gained from psychological and physiological studies (Borg, 1998). The reliability and validity of this scale have been reported as a subjective rating score to physical workload levels since, according to Borg (1998), bicycle ergometer physical workload results showed that the coefficient correlation between 100 Watts and the RPE scale is 0.70 and 0.87 with 150 W. Furthermore, other studies have correlated highly with increasing levels of workload, HR, VO_2 and RPE scores, which are linear in shape (Borg, 1998).

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 2.5 Rating of perceived exertion (RPE) scale range. (adapted from Borg, 1998)

The category ratio (Borg-CR10) scale was created for a similar purpose to the RPE scale, which was to evaluate the intensity of physical activities related to physiological functions. The main feature of the CR10 scale is reflecting the pain attribute that occurs to sensory perceptions due to the highest intensity exercises (Borg, 1998). The scale ranges from 0 “Nothing at all” to ● “Absolute maximum.” The scale ends with a dot point that means any score more than 11 is an unexpected extreme load or pain (Figure 2.6). Like the RPE scale, the validity and reliability of the CR10 have been proven in several studies. There is a high correlation between increasing levels of CR10 scores and increasing physical activity intensity on a bicycle as HR increases (Borg, 1984). Borg mentioned that the correlations between physiological variables such as HR (r = 0.91), blood lactate, and systolic blood pressure (r = 0.78) and the CR10 scale are significant and linear (Borg, 1998, p.43). Moreover, the correlation between CR10 and RPE is significantly high (Borg, 1998). The scale has been used widely in different experimental studies in order to reflect high levels of physical workload and musculoskeletal pain due to activity (e.g. Mehta and Agnew, 2011).

0	Nothing at all	“No P”
0.3		
0.5	Extremely weak	Just noticeable
1	Very weak	
1.5		
2	Weak Light	
2.5		
3	Moderate	
4		
5	Strong Heavy	
6		
7	Very strong	
8		
9		
10	**Extremely strong “Max P”**	
11		
ϟ		
●	Absolute maximum	Highest possible

Figure 2.6 Borg-CR10 rating scale range. (adapted from Borg, 1998)

Visual Analog Scale (VAS)

The VA scale uses a subjective measure to assess the exertion and pain levels that occur due to physical actions (Price, 1994). The VA scale has been used in studies that investigated the impact of physical demands on muscle pain and problems (DiDomenico and Nussbaum, 2011; Wilson and Jones, 1989). This scale is more suitable in studies that aim to find individual differences in aspects of pain due to physical activities. The VA scale is presented as a 10cm solid line and ranges from “no exertion at all” to “maximal exertion” as illustrated in Figure 2.7. Participants can use this scale by marking a small line on the scale, depending on his/her perception about the physical workload and pain (Price, 1994).

Harms-Ringdahl et al. (1986) found that both scales, VA and CR10, are reliable to assess the strain and pain in arms (elbows) due to physical loads. The reliability and validity of the VA scale in measuring pain has been proven in different studies (Neely et al., 1992). The VA scale has an incremental curve correlation with physiological variables such as HR and blood lactate (BL) as the physical workload increased (Neely et al., 1992).

Figure 2.7 Example of VA scale rating

Ueda et al. (2006) concluded that participants gave a higher pain VA score for cycling compared to running. They also asserted that a linear correlation had been found between pain levels, VA score, HR and VO_2. The VA scale has been used in different studies including the use of the bicycle ergometer, treadmill, and materials handling (Neely et al., 1992) to assess the pain that occurs due to maximal exercise levels. No study has used this scale in physical and mental task interactions.

2.7.3 Combined Measurement of Physical and Mental Workload Interaction

As presented in sections 2.7.1 and 2.7.2, different techniques are used to measure mental workload and physical workloads. Also, these sections discussed joint physiological measures such as HR, HRV and blood pressure, which are used to assess the effects of overall workloads on individual physiological arousal. The most important reasons for implementing a number of these measures is to get accurate results between different workload interactions, since the physiological measures are more sensitive than other measurement techniques such as performance and rating scores, in combined physical and mental workload situations (Fredericks et al., 2005). The measurements of overall workload in tasks that impose both physical and mental demands simultaneously have received little attention. Therefore, this section presents another measure that is useful in measuring physical and mental workload interactions. The measure is brain oxygenation changes by Near-Infrared Spectroscopy (NIRS). The sections below explain this measure in detail and the reasons for its selection.

2.7.3.1 Brain Activity and Workload

One recent method in neuroergonomic science is measuring the impact of workload on brain activity (Parasuraman and Wilson, 2008). Brain activity is measured to assess the impact of workloads on cognitive functions and information processes such as seeing, remerging, and deciding, which are induced by mental workload and physical activity such as lifting objects, grasping, and body movements (Parasurman and Rizzo, 2007). Furthermore, the voluntary control of human actions or physical tasks, combined with mental load (cognitive, perceptual and affective processes), is one of the primary functions of the brain (Karwowski et al., 2003). As a result, tasks that include physical and mental demands might place a heavy load on the brain function capacity of the operator. Consequently, operator performance could decrease and limit brain capability. The relationships between brain function against PWL and MWL have been discussed separately (Karwowski et al., 2003).

It has now become easier to measure oxygenation changes in the frontal region of the brain and blood flow in the brain due to technological improvements (Banaji et al., 2008). In fact, brain activity has been used in different studies as a new objective measure to reflect the impact of cognitive workload in different ways. It has been used in several studies, such as aviation and driving, to reflect the amount of brain activation that occurs due to different mental tasks such as visual attention (Parasurman and Rizzo, 2007). A number of methods have been developed to assess brain activity during mental and physical tasks. These include Transcranial Doppler Sonography (TCD), Near-infrared spectroscopy (NIRS), Electroencephalography (EEG) and Functional Magnetic Resonance Imaging (fMRI) (Parasurman and Rizzo, 2007).

NIRS is an effective and non-invasive technique that permits the measurement of the percentage of oxygenation and deoxygenated haemoglobin in brain blood and muscles during task performance and at rest (Perrey et al., 2010). Moreover, NIRS can be used on the prefrontal cortex of the brain to examine the cognitive ability (e.g., judgments) of operators under physical conditions (Perrey et al., 2010). Rupp and Perrey (2008) stated that the NIRS technique is one of the faster methods of measuring oxygenation fluctuation in the brain blood that is related to neuronal force and workload capacity in healthy and unhealthy individuals. NIRS reflects the load on brain activity induced by mental demands and physical activities, by recording the oxygenation changes in the frontal area of the brain. The prefrontal cortex is part of the frontal lobe of the brain (Huey et al., 2006) and it is considered to be an important region of the brain because it allows humans to control the highest level of mental processes, including thinking, planning, working memory, attention, and concept formation (Huey et al., 2006).

NIRS records the changes in oxyhaemoglobin (O2Hb) and deoxyhaemoglobin (HHb) values, or records the region tissue oxygenation (rSO2), which is the ratio of O2Hb and tHb multiplied by 100, where tHb is the total haemoglobin (the sum of O2Hb and HHb) (Moritz et al., 2006). The reliability of NIRS in estimating the oxygenation changes in the brain has been validated in different experimental studies including with pilots and arithmetic tasks (Hershfield et al., 2009; Perrey et al., 2010).

The NIRS technique is a unique brain activity measure that can evaluate the effect of workloads of both mental and physical tasks on attentional resources (Perrey et al., 2010). It can record the percentage of oxygen in the blood delivered to the frontal region of the brain, a region that controls all cognitive thinking and processing, during task performance. Therefore, the oxygenation level can shows the mismatch between the oxygen available to the brain and the amount of oxygen needed to meet the task’s demands. So, increasing levels of mental workload will lead to increased oxygen requirements to meet the increased demand; thus the activation and the percentage of oxygenation in the brain will increase. It has been suggested that some levels of physical workload can improve and support attentional resource capacity during cognitive functions through increasing the oxygen in the brain which is required by the increased level of mental workload (Perrey et al., 2010). According to Antunes et al. (2006), some levels of physical activities could increase the blood flow to the brain, so the oxygen is increased in the frontal area of brain, and so the percentage of oxygenation changes in the brain is reduced due to the need to balance the amount of oxygen available in the brain and the amount needed to complete the mental task demands. Therefore, the NIRS method was chosen in this research to assess the effects of different workload interactions on attentional resources during brain activity. This unique neuroergonomics method could reflect the potential impact of physical workload on information processing (Karwowski et al., 2003) and this method is easy to set up and use to measure brain activity during physical activity (Perrey et al., 2010). So, while previous physiological measures mentioned can be used to reflect the influence of physical and mental workloads on arousal and the cardiovascular system, NIRS was used to measure rSO2 in this thesis to reflect the stress on attentional resource capacity through the percentage of oxygenation change during brain activation. Thus, this measure offers an exciting possibility of showing how physical workload can support and assist cognitive processing through increasing the level of oxygen in the frontal area of the brain.

Most researchers have used NIRS to assess oxygenation changes in the muscles due to a physical workload such as during materials handling and exercises (Rupp and Perrey, 2008). They have illustrated that increasing the level of exercise leads to high levels of blood oxygenation changes (O2Hb increased and HHb decreased) in forearm muscles during exercise. They said that muscle activation increased because there is no balance between the oxygen in the muscles and the oxygen needed to meet increasing exercise. However, Perrey et al. (2010) mentioned a phenomenon that exists in the prefrontal cortex in the brain during mental and physical tasks and it may be that physical and mental workloads are a challenge to oxygenation of the brain. Therefore, further research to evaluate the impact of physical and mental demands on brain oxygenation changes is necessary in order to determine whether physical exercise can reduce the loads on the brain during information processing by increasing the levels of oxygenation delivered to brain (Perrey et al., 2010).

Numerous researchers have studied the relationship between brain activity and blood oxygenation and blood flow velocity during cognitive task performance (Warm et al., 2008). Generally, it has been concluded that the rise in blood oxygenation changes in the prefrontal cortex in the brain is associated with increasing levels of mental workload, which means that as activation of the brain increases, there is a reduction of available oxygen in the brain and so performance decreases (Kikukawa et al., 2008; Perrey et al., 2010). It has been reported that increasing the levels of arithmetic task demands led to an increase in the percentage of blood oxygenation in the brain by increasing O2Hb and decreasing HHb (rSO2% increasing) (Perrey et al., 2010).

That means the percentage of oxygen in the brain is not enough to meet the oxygen needs that occur due to incremental mental demands. Furthermore, according to Kikukawa et al. (2008), one researcher studied the oxygenation of brain activity in the prefrontal cortex while the participants were performing pilot tasks. The researcher found that increased brain activation during increasing levels of attention (take-off situation) increased the O2Hb and decreased HHb (rSO2% increased); that means the oxygenation percentage increased due to increasing levels of mental demand. Hershfield et al. (2009) reported that increasing the demand of a visual detection task placed heavy cognitive load on information processing, reflected by an increase in the percentage of oxygenation changes during brain activity. They stated that increased mental demands led to increased brain load, which resulted in a mismatch between brain oxygen utilisation and local brain oxygen delivery. As stated before, increasing the intensity level of physcial activities leads to a decrease in oxygen in most body muscles (e.g., arms and legs). Therefore, the activation increases in the muscles due to oxygen reduction to meet the physical loads. As a result, the oxygen that is delivered to the brain reduces and information processing becomes slower, and the percentage of oxygen in the brain reduces, thus performance decreases (Perrey et al., 2010).

Brain activity has been used to measure and determine gender differences during mental task performance. According to Gur et al. (2000), increasing oxygenation in the brain is usually associated with better performance in both genders. It has been mentioned that it is necessary to control the balance between the operator’s brain function capability and task demands (Karwowski et al., 2003; Perrey et al., 2010). This leads to a good match between the oxygen delivered to the brain and oxygen needed to meet demands. Therefore, the oxygenation change measures (i.e. frontal cortex oxygenation in the brain) will be observed to investigate the effect of this interaction on brain activity (i.e. processing information). In addition, as one of the objectives of this thesis is to determine the impact of physical and mental workload interaction on human attentional resource performance, the oxygenation changes measure (i.e. frontal cortex oxygenation, regional cerebral oxygen saturation, rSO2) in the brain will be observed to investigate the effect of this interaction on brain activity (i.e. processing information). Therefore, this measurement could help researchers to determine at which level of mental and physical combination brain activity yields an optimum performance.

2.8 CONCLUSION

In this literature review, the researcher has aimed to understand the multitask workload paradigm and its relationship with performance; therefore, the mental workload concept and methodologies were explored. Following that, attentional resource models were covered in order to understand the integration between mental demands, resources capacity, and performance. Physical workload definitions and methodologies were described. Then the literature review shifted to the major issue in the thesis that clarified physical and mental workload interactions against performance and gender differences in situations of multitask demands. A brain activity measure and workload interactions were discussed to identify a new method that determines brain activity stress during dual-task scenarios.

As stated previously, in particular, in section 2.6, previous studies have not adequately accounted for the impact of physical activities on cognitive tasks and mental functions. As previous studies have not considered multiple attentional resources, researchers' findings on the effect of physical and mental demands on performance have been inconsistent. That is because they did not consider different resources and information processes (e.g., verbal and spatial resources) and also because they used simple mental tasks. In addition, in most studies the authors investigated the effects of various levels of physical exercise on one level of mental workload (Mozrall and Drury, 1996). The gender aspect has also been neglected in previous studies, which may have affected their findings (Yagi et al., 1999). Measurements of general workload for tasks that require both physical and mental input are rare; in particular, the effect of both workloads on physiological arousal and on the cardiovascular system can help researchers separate the effects of physical and mental workload. In addition, there is a lack of data on the effect of physical and mental workload interactions on brain activity, leading to a lack of understanding of how physical workload facilitates information processing through the percentage of oxygenation changes during mental tasks.

The following points show how the thesis questions were set up.

First, most previous authors have investigated the influence of physical and/or mental workload on individual performance independently. In addition, most of the papers that examine the impact of physical workload on cognitive tasks did not find consistent results (Tomporowski, 2003). Some researchers found that physical demands did not impact cognitive functions (e.g., Perry et al., 2008), whereas others concluded that the correlation between physical workload and mental tasks is an inverted-U shape (e.g., Reilly and Smith, 1986). In addition, most of the mental tasks that have been used in these studies are simple (reaction time tasks) and not sufficiently selective to evaluate changes in specific higher mental capabilities that may occur concurrently with physical activities (Dietrich et al., 2004). It seems that the gap in previous studies is that most of them used simple visual and auditory tasks (RT tasks), which may affect these studies' results. Therefore, it is necessary to use more complex mental tasks to present the impact of physical and mental workloads on performance.

Second, the other important fact derived from this chapter is that the current model of mental workload (i.e. multiple resources model by Wickens (1984)) does not account for the influence of physical interactions with mental loads on attention capacity and performance. Most of the studies examined the impact of mental demands independently of this model. Therefore, it seems there is a gap between the combination of the mental workload model (i.e. multiple attentional resources model) and physical workload. Consequently, based on previous points, it is worthwhile creating a model in order to understand how the physical workload mechanism interacts with the multiple resources model.

Third, gender difference is one of the limitations of previous studies. According to Yagi et al. (1999), differences between males and females in performance during physical and mental task interactions exist, but they are not uniform because simple mental tasks cannot show such differences as effectively as complex mental tasks.

Thus, the current thesis aims to explore the gender differences while performing dual tasks, to learn how both males and females deal with a dual task paradigm and explore if there are differences between them to help to generalise the data.

Fourth, there are few evaluations of overall workload in tasks that require concurrent mental and physical activities (Fredericks et al., 2005). Most researchers focus on physiological measures, such as HR and blood pressure, and yet these measures are useful to reflect the effect of physical and mental workload in dual-task situations. Thus, this research uses these measures for that purpose. Furthermore, a balance between task workload and brain activity is required to improve individual performance. The changes in oxygenation in the frontal lobe and motor cortex in the brain may reflect workload level and capacity (Perrey et al., 2010). Still, no study has yet investigated the impact of physical and mental workload together on attentional capacity by measuring brain activity (Perrey et al., 2010). Therefore, the change in regional oxygen saturation (rSO2) measure in the brain was used to reflect brain activity during workload interactions. This measure could help researchers to determine at which level of input combination brain activity yields an optimum performance. Furthermore, it could become a useful indicator that might allow designers to predict the brain function capacity of the human against task workload in the future.

This PhD thesis has therefore developed a new model (see Figure 2.8) which is based on the multiple resources model (MRM) of Wickens (1984) and which seeks to explain the mechanisms of different levels of physical workload and mental demands interaction with attentional resources, in order to identify how physical loads can facilitate different types of information processing during these interactions.

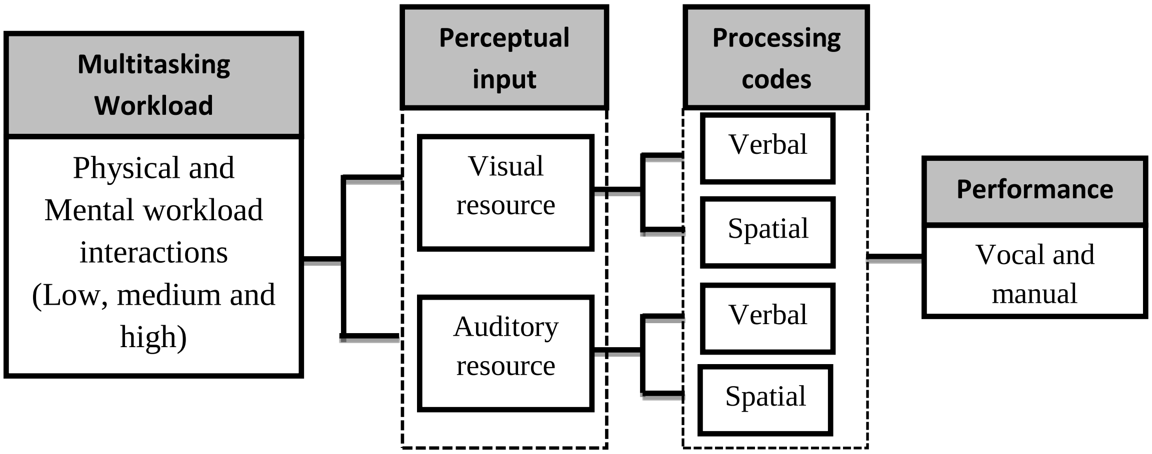


Figure 2.8 The proposed new model of the interaction of physical and mental workloads on attentional resources

The general research questions and hypotheses that were derived from this chapter are:

✓ How do different levels of physical and mental workload combinations influence visual and auditory tasks?

- Verbal vs. spatial visual tasks.
- Verbal vs. spatial auditory tasks.

✓ On what attentional mechanism does physical workload operate?

- Verbal vs. spatial visual tasks.
- Verbal vs. spatial auditory tasks.

Expectation: That a medium level of physical workload leads to better performance visual, spatial and verbal tasks. Moreover, it also leads to better performance in auditory mental task in both verbal and spatial tasks through increasing level of arousal level, which in turn increases level of attentional resources capacity. Also, the low and medium physical workloads will be leads to better performance in visual and auditory tasks through supply more blood flow to the brain and translated more oxygen to the brain. Therefore, the incremental increasing in level of physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in regional cerebral oxygen saturation (rSO2) so, that will reduces the oxygen differences in the brain that occurs due to increase mental workload However, spatial mental tasks performed concurrently with physical workloads become more difficult than verbal mental tasks with physical workloads.

Justification: the relation between physical demands and cognitive performance is an inverted-U shape (Mozrall and Drury, 1996), as it is between mental workload and performance (Young and Stanton, 2002[b]). According to Reilly and Smith (1986), a moderate level of physical exercise (38% VO2 max) facilitates visual spatial tasks. They also found that the medium level supports simple (verbal) mathematical task performance. Moreover, it has been reported that a medium level of physical activity supports the simple auditory level of tone identification task performance (Yagi et al., 1999). Audiffren et al. (2009) concluded that a medium level pedalling exercise improves simple auditory tasks involving ascending numbers. However, currently there is no study that has investigated the different levels of physical and mental workloads on more complex types of mental tasks.

The incremental increase in physical workload will lead to an increase in physiological arousal level (Audiffren et al., 2009); thus, moderate levels of physical workload will improve cognitive performance, since there is a correlation between arousal level and performance; this is the same as between mental demands and performance, which is curvilinear (Young and Stanton, 2002[b]).

Increasing levels of mental workload tend to increase the gap between oxygen available to the brain and the amount of oxygen needed to meet this workload, so brain activity will increase by increasing level of regional cerebral oxygen saturation (rSO2) to ensure the supply of more oxygen to the brain (Kikukawa et al., 2008). In addition, some levels of physical exercise raise the amount of blood that is transported to the brain, so increasing the oxygen and therefore improving information processing (Antunes et al., 2006). According to Perry et al. (2009), there is a potential impact on brain activity capacity during a high level of physical workload that may place stress on the brain while performing cognitive tasks.

- ✓ Are there any significant gender differences in situations of physical and mental task interactions?

Expectation: Differences between males and females will appear, in particular, during high levels of physical and mental combination, and females' performance will be better than males in verbal, visual and auditory tasks whereas males will outperform females in spatial tasks. However, at the low and medium levels of interaction, the difference will be disappearing.

Justification: Usually, in simple cognitive tasks, the gender difference disappears (Halpern, 2000). In addition, during low and medium levels of physical exercise, information processing is improved and facilitated through increasing level of arousal level, which in turn increase level of attentional resource capcity and then leads to better perfromance in both genders, and differences disappear (Yagi et al., 1999). However, performance during intensive physical activity will be significantly different due to the variation between genders in physical strength and capacity (Borg, 1998). Females generally perform better than males in verbal tasks whereas males do better in spatial tasks (Koscik et al., 2009), since the strategy of men in processing the orientation of spatial figures is quicker than females due to genetic differences in brain structure (Skrandies et al., 1999).

Finally, to show the validity of this PhD thesis model, this research aims to implement a field study of an assembly production line to validate the new model in a real-world situation and to find out how the mental and physical workload in assembly tasks can impact operators' attentional resources in order to achieve valuable applied recommendations.

3

CHAPTER 3: METHODOLOGY AND EXPERIMENTAL PROGRAMMES

3.1 OVERVIEW

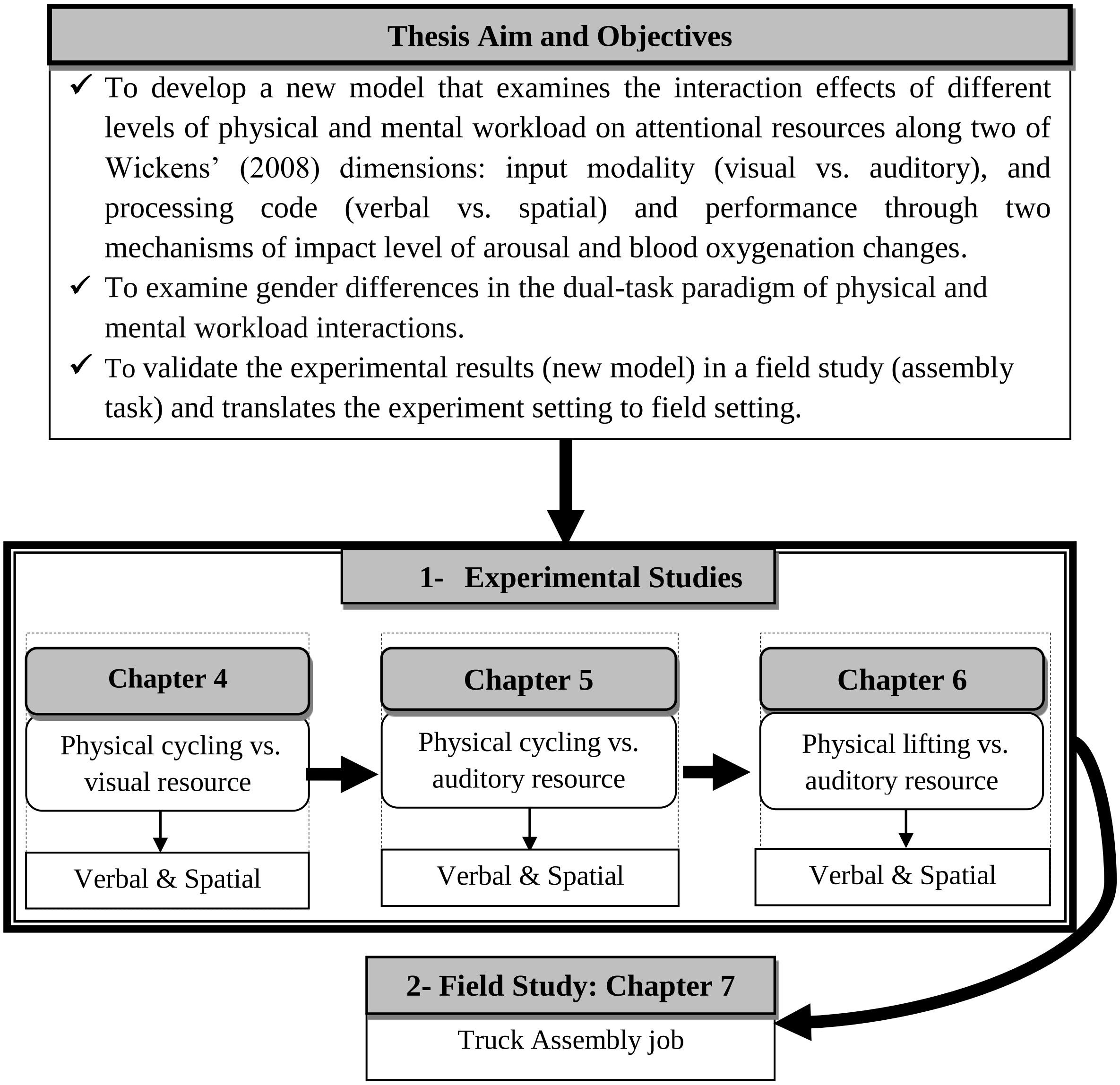
As indicated in the previous chapter, most research has focused separately on the impact of mental and physical workload on performance. In addition, previous studies have not considered the impact of physical workload on mental workload models: in particular, the multiple resources model, since they focused on the influence of mental task demands on attentional resources. In other studies, DiDomenico and Nussbaum (2008, 2011) researched the impacts of a combination of physical and mental demands on mathematical cognitive tasks, but they did not consider the attentional resources along two of Wickens' (2008) dimensions: input modality (visual vs. auditory) and processing code (verbal vs. spatial). Therefore, the aim of this thesis is to establish a new model which determines the mechanism of physical and mental workload interaction with the multiple resources model (see section 2.4.3), visual mental tasks (verbal and spatial resources), and auditory tasks (verbal and spatial resources). Furthermore, this thesis aims to apply a practical implementation for this new model in a real-life situation (i.e. an assembly job) in order to validate the model and make valuable recommendations for the design of such jobs. The current chapter clarifies the experimental study programmes and sequences, including the aims and methodology of these experiments. Finally, this chapter explains the set up in the field, with its aims and methodology.

3.2 INTRODUCTION

This chapter classifies the experimental programmes, the designs and conditions of laboratory experiments, and the sequence of experiments. In addition, it illustrates the field study design and conditions that were implemented to validate the new model derived from laboratory experiments. In general, most physical and mental workload studies have not systematically investigated the impact of interactions between physical and mental demands on individual performance (DiDomenico and

Nussbaum, 2008; Perry et al., 2008). In fact, most of the results of previous studies on the effects of physical workload on cognitive tasks and processes are not uniform (Tomporowski, 2003; Tomporowski and Ellis, 1986), since these studies used simple mental tasks (e.g., reaction time tasks) (Joyce et al., 2009). The most important point that these previous studies neglected is the impact of physical workload on the Wickens’ (2008) multiple resources model (Mozrall and Drury, 1996). As a result, this research aims to set up a new model that describes the effect of different levels of physical and mental workload interactions on the attentional resources model.

In order to achieve to these aims and objectives, the methodology is divided into two parts as illustrated in Figure 3.1. First, Chapter 4 aims to investigate the impact of physical and mental workload combinations on visual resources (verbal and spatial resources). Then, Chapter 5 clarifies the influence of workload interactions on auditory resources, both verbal and spatial. In both chapters the physical task was produced by a stationary bicycle ergometer. Following the results of Chapters 4 and 5, the physical workload was changed to lifting boxes, together with mental auditory tasks, as explained in Chapter 6. The reason for using lifting tasks is that they are more applicable to real jobs (i.e. an assembly job) and auditory tasks were used because it is difficult to set up visual tasks concurrently with a lifting task. Following the experimental studies, Chapter 7 describes field studies that evaluated the impact of physical and mental workloads during a truck assembly job in order to validate the new model that resulted from the previous three chapters, and in order to produce valuable design advice for this job. The integrated results of the experimental and field studies are presented in Chapter 8.


Thesis Aim and Objectives

- ✓ To develop a new model that examines the interaction effects of different levels of physical and mental workload on attentional resources along two of Wickens' (2008) dimensions: input modality (visual vs. auditory), and processing code (verbal vs. spatial) and performance through two mechanisms of impact level of arousal and blood oxygenation changes.
- ✓ To examine gender differences in the dual-task paradigm of physical and mental workload interactions.
- ✓ To validate the experimental results (new model) in a field study (assembly task) and translates the experiment setting to field setting.

Figure 3.1 Thesis methodology outline

As illustrated in figure 3.1, the thesis involved three laboratory experiments. These experiments were conducted in order to understand and to create a new model that examines the impact of different levels of physical and mental workload combinations on perceptual inputs of a multiple attentional resources model (Wickens, 1984) that includes visual resources (verbal and spatial) and auditory resources (verbal and spatial). However, the first experiment (Chapter 4) was conducted to investigate the effects of physical cycling and mental workload interactions on the performance of visual tasks (visual arithmetic task-verbal task and spatial figures task-spatial task). In the following chapter, the second experiment (Chapter 5) was carried out to examine the influence of physical (cycling task) and mental workload combinations on two auditory tasks: an arithmetic task (verbal task) and a tone localisation task (spatial task). Then, in Chapter 6, the third experiment was implemented; however, in this experiment, the physical task was changed to lifting boxes instead of cycling because this type of physical task is more appropriate to a real domain job, in particular, an assembly job. Therefore, this chapter aimed to examine the impact of physical lifting and mental workload combinations on auditory tasks (arithmetic and tone localisation tasks).

A novelty in these three experiments is that different methods of measuring physical and mental workload combinations were used, such as the brain activity method described in Chapter 2. Since most previous researchers have tended to use limited methods to assess the impact of physical and mental workloads (DiDomenico and Nussbaum 2008), they have only focused on performance measures (e.g. number of correct responses and reaction times) and heart rate as physiological measures (Yagi et al., 1999). In addition, Perry et al. (2010) suggest using various methods to assess the effects of both workloads on attentional resources and physiological states; given that physical workload can impact on cognitive functions through the physiological arousal level and brain oxygenation changes. However, as mentioned in Chapter 2 (Section 2.7), numerous methods can be employed to evaluate the impact of mental and physical workloads on performance. For reasons which are explained in section 3.3.2, this research utilised four main measures to assess the effects of physical and mental workloads: first, a performance measure (accuracy and time of correct responses); second, physiological measures, including heart rate, heart rate variability, blood pressure, and rate-pressure product; brain activity, via a new neuroergonomics method called Near-Infrared Spectroscopy (NIRS); and finally, subjective assessment tools such as the NASA-TLX rating score and Borg’s scores (CR10 and RPE). After completing the three laboratory experiments, the research moved to the field study (Chapter 7) of a product assembly job. This field study was conducted at a Mercedes truck assembly factory. The study aimed to validate the new model that was created on the basis of the experimental results.

This chapter explains the experimental study programmes, design, and conditions undertaken in this research and the sequences of these experiments. Also, the design and set-up conditions of the field study are described.

3.3 FIRST PART: METHODS OF EXPERIMENTAL STUDIES

The current research conducted three laboratory experiments:

- ***First experiment (Chapter 4):*** Investigation of the impact of cycling exercise and visual mental task workload interactions on visual resources.
- ***Second experiment (Chapter 5):*** Examination of the effects of cycling exercise and auditory task workload on auditory resources.
- ***Third experiment (Chapter 6):*** Examination of the mechanism of a lifting task workload and auditory task demands on auditory resources.

3.3.1 Experimental Design

The design across all laboratory experiments was the same. Each experiment was divided into two parts, designed to address whether physical workload interacts with verbal attentional resources (mental verbal task – experiment 1) and/or spatial resources (mental spatial task – experiment 2). The participants for each experiment were divided into two groups of 15 (one group for experiment 1 and another for experiment 2, in a between-subjects design), aged 25 –35, with an equal balance of male and female participants in each group. A different group of participants was used for each experiment. In each experiment, participants were asked to perform a physical task (under controlled conditions) concurrently with a mental task under nine levels of workload in a 3x3 design (low, medium and high levels for both physical and mental tasks). Table 1 illustrates the nine conditions of interaction between the physical and mental tasks. The hypotheses across all three experiments were similar and derived from the literature review as mentioned in Chapter 2 section 2.8.

Table 3.1 The nine conditions of interaction for the physical load and mental workload and the associated hypotheses in each condition

		Mental Visual OR Auditory Workload (MWL)		
		Low MWL	**Medium MWL**	**High MWL**
Physical Workload (PWL)	**Low PWL**	Participants' performance will be worse	Participants' performance will be worse	Participants' performance will be worse
	Medium PWL	Participants' performance will be better	Best performance will occur under this condition	Participants' performance will be worse
	High PWL	Participants' performance will be worse	Participants' performance will be worse	Worst performance will occur under this condition

Repeated measure analysis was used for the *within subject factor* (physical and mental workload) and *between subject factors* (type of mental tasks and gender). The experiments were focused on the effect of physical and mental workload interactions as the main aim of the thesis. Therefore, the experiments were different in the types of mental tasks and/or physical tasks performed by the subjects, as shown in Table 3.2, which illustrates the types of physical and mental tasks that were used in each experiment. The gender factor was considered in this thesis since, according to the literature review (Chapter 2); there is a lack of attention in previous studies given to the gender differences aspect. Most of these studies have not covered gender differences while performing physical and mental tasks concurrently (Yagi et al., 1999). Therefore, this research aims to determine gender differences in performing physical and mental tasks in order to generalise the output data and fill in this gap in the literature. However, this experiment was focused on the effect of physical and mental workload interaction factors; interaction influence was not considered, as the main aim of experiments was to find the effect of workload interactions on visual and auditory task performance.

First experiment (Chapter 4) involved two sub-experiments: physical cycling task versus visual mental arithmetic task (visual-verbal task - experiment 1) and physical cycling versus spatial figures task (visual-spatial task- experiment 2).

Second experiment (Chapter 5) involved two sub-experiments: physical cycling task versus auditory mental arithmetic task (auditory-verbal task - experiment 1) and physical cycling versus tone localisation task (auditory-spatial task- experiment 2).

Third experiment (Chapter 6) involved two sub-experiments: physical lifting boxes task versus auditory mental arithmetic task (auditory-verbal task - experiment 1) and physical lifting boxes versus tone localisation task (auditory-spatial task- experiment 2).

Each mental task included three different levels of difficulty and three different loads (Table 3.2). The details of these tasks and levels of difficulty are presented later, in the experiment chapters.

Table 3.2 Physical and mental tasks in each experiment and their difficulty levels

Experiment	Physical Task	Mental Tasks	
1	**Bicycle Ergometer** - 20% of maximum workload capacity **(low level)** - 50% of maximum workload capacity **(medium level)** - 80% of maximum workload capacity **(high level)**	**Visual-verbal task** **(Arithmetic task)** - Low level - Medium level - Difficult level	**Visual-spatial task** **(Spatial figures task)** - Low level - Medium level - Difficult level
2	**Bicycle Ergometer** Same levels as experiment 1	**Auditory-verbal task** **(Arithmetic task)** - Low level - Medium level - Difficult level	**Auditory-spatial task** **(Tone localisation)** - Low level - Medium level - Difficult level
3	**Lifting boxes** - 8% of body weight **(low level)** - 14% of body weight **(medium level)** - 20% of body weight **(high level)**	**Auditory-verbal task** **(Arithmetic task)** - Same levels in experiment 2	**Auditory-spatial task** **(Tone localisation)** - Same levels in experiment 2

3.3.2 Selection of Output Measures

All experimental studies depend on quantitative data collection. Previous research studies are usually divided workload measures into objective measures such as performance (e.g. accuracy and time of task), physiological measures (e.g. heart rate and blood pressure), and subjective assessment tools such as NASA-TLX, Borg-RPE and Borg-CR10 scores (Fredericks et al., 2005). The dependent measures (output measures) were divided into three main measures; the following sections present the selected measures applied in the experiments, as illustrated in Table 3.3. The same measures were taken across all three experimental studies. Moreover, the details and reasons for the methods and measures selected (see section 2.7) are presented below

Table 3.3 Selected measures that were used across all experiments.

Measure Name	Descriptions	Objectives
Performance measures	accuracy and time of task (total cumulative time of the task)	They were used to reflect the level of responses during different conditions of physical and mental workloads interactions
a) Physiological measures	heart rate (HR), heart rate variability (HRV),and blood pressure (BP)	HR was used to reflect the alterations in arousal level during workload interactions conditions also, HR, HRV and MBP were used to reflect the changes among workloads interactions during the conditions
b) Brain activity measure (physiological measure)	measure blood oxygenation changes in the brain by recorded Region tissue oxygenation (rSO2)	rSO2 was used to reflect the alterations in brain oxygenation and changes and blood flow among workloads interactions during the conditions
Subjective assessment tools	NASA-TLX to measure mental workload	To reflect the alterations in mental workload during the conditions of workload interactions
	Borg RPE and CR10 scales were used to assess the physical workload.	To reflect the alterations in physical workload during the conditions of workload interactions

This study uses different methods to evaluate the effects of physical and mental workload interactions on individual performance. Most previous research has used performance and heart rate (Fredericks et al., 2005). Therefore, the current thesis uses three methods: (1) performance (accuracy and time of task), (2) physiological parameters (HR, HRV, and MBP), and brain activity (rSO2) (3) subjective assessment tools (NASA-TLX scale, Borg's CR10 and RPE scales).

3.3.2.1 Performance Measures

This measure was reflected by measuring the *accuracy* and *cumulative time of task (task time)* to the mental tasks for each participant under each condition of workload interaction. The accuracy and time of task were used to reflect the changes in physical and mental demand combinations. It has been reported that the accuracy and total time of task to mental and physical tasks varies by workload difficulty (Audiffren et al., 2009; DiDomenico and Nussbaum, 2008, 2011; Perry et al., 2008; Reilly and Smith, 1986). The accuracy was calculated through the number of correct responses, which was recorded automatically by software, and the time of task was recorded for each participant.

3.3.2.2 Physiological Measures

As mentioned in sections 2.7.1 and 2.7.2, there are a number of combined physiological variables that measure the changing workload of physical and mental tasks. In this thesis, the physiological measures depend on sensitivity to both workload interactions and the measures that were selected in order to assess the physiological arousal changes during levels of workload combinations. Therefore, three indicators were chosen to measure the physiological effects of physical and mental workload interactions: heart rate (HR), heart rate variability (HRV), and mean blood pressure (MBP). All these measures were recorded continuously during the tasks performed for each condition.

Heart rate has been widely used to assess physical and mental demand interactions (Audiffren et al., 2009; Audiffren et al., 2008). It has been reported that HR is sensitive to changes in mental workload (Hwang et al., 2008) and also, it is sensitive to physical workload alterations and it significantly increases as physical loads increase (Borg, 1990; Sammer, 1998). In addition, according to Veltman and Gaillard (1996), HRV decline is associated with mental workload increase and is sensitive to complex cognitive tasks. Furthermore, HRV is sensitive to incremental physical exercise, since it relates to heart rate changes (DiDomenico and Nussbaum, 2011; Rennie et al., 2003). Therefore, HR and HRV are both reliable and valid to assess mental and physical workload interactions.

The blood pressure measure has been successfully influenced by different mental tasks (Hwang et al., 2008; Veltman and Gaillard, 1996). Fredericks et al. (2005) found that systolic blood pressure significantly increased when physical and mental workload difficulties increased (2001, 2005). They reported that blood pressure is sensitive to physical activity changes and also that it changes when cognitive task demands increase. The reliability and validity of BP as a measure of physical workload have been indicated by Borg, who reported that increasing levels of physical exercise lead to high systolic and diastolic blood pressure (Borg, 1987). More details are presented in Chapter 2, sections 2.7.1 and 2.7.2. Thus, this research recorded the mean blood pressure measure continuously to reflect the physiological load of each task condition. These physiological measures were used because they are more sensitive to workload changes than other measures such as performance and subjective assessment tools (Fredericks et al., 2005; Hwang et al., 2008). In addition, the experiments involved different conditions of workload interactions, so these measures should support finding the differences between these levels and also support finding the gender differences more than other measures, since the physiological differences between males and females are more distinct than other measures (Borg, 1998; Yagi et al., 1999).

3.3.2.3 Brain Activity Measure

Brain activation during physical and mental task workload interactions was measured by using a new neuroergonomics method: Near-infrared spectroscopy (NIRS). The neuroergonomics method uses brain activity during the dual-tasks paradigm as an indicator of attentional resource capacity (Parasurman and Rizzo, 2007); most authors have determined brain activity during mental tasks, but no study has determined the activation state of the brain during both workloads (Perrey et al., 2010). So, this research used NIRS to assess the brain’s activity state during combined physical and mental demands. This method has been used widely in various studies to measure blood oxygenation changes in the brain during cognitive tasks (Parasurman and Rizzo, 2007; Perrey et al., 2010). Region tissue oxygenation (rSO2) in the brain was recorded continuously during tasks performed to reflect the percentage of blood oxygenation in the cortex region of the frontal area of the brain that occurs due to the physical and mental demands of attentional resource performance. It has been shown that the percentage of oxygenation variation in the brain increases as mental workload increases (Hirschfield et al., 2009; Kikukawa et al., 2008). Therefore, this measure reflects the reduction in oxygen utilised by the brain; that is, a mismatch between the existing oxygen in the brain and the amount of oxygen it needs to meet the mental workload. Perrey et al. (2010) reported this phenomenon in the prefrontal cortex of the brain during mental and physical tasks, and it may be that physical and mental workloads of certain occupations present a challenge to oxygenation of the brain. Therefore, this research intends to evaluate the impact of physical and mental demands on brain oxygenation changes, which is necessary in order to determine if physical exercise can reduce the loads on the brain during information processing by increasing the levels of oxygenation delivered to the brain (Perrey et al., 2010). The validation and reliability of NIRS in estimating the oxygenation changes in the brain has been shown in different experimental studies involving, for example, pilots and arithmetic tasks (Hirshfield et al., 2009).

3.3.2.4 Subjective Assessment Tools

NASA-TLX has been shown to reflect mental and physical workload combinations (DiDomenico and Nussbaum, 2008; Fredericks et al., 2005; Hart and Staveland, 1988). These studies have concluded that increasing levels of mental and physical workloads lead to higher TLX scores. This has been commonly used to assess mental demand difficulty changes (Hart and Staveland, 1988; Patten et al., 2004; Rubio et al., 2004). The scale is sensitive to changes in overall mental workload at low, medium, and high levels, and it has been used in several studies in single- and dual-task environments (Hart, 2006; Rubio et al., 2004). The validity and reliability of the TLX has been supported by numerous experimental results (Hart and Staveland, 1988; Rubio et al., 2004). Therefore, the NASA-TLX score was used to measure the mental workload and overall workload (physical and mental workload) and to reflect the participants' perceived overall workload. The participants completed the rating score directly after each set of concurrent physical and mental tasks. Furthermore, the mental demand dimension (MD) and physical demand dimension (PD) in NASA-TLX were analysed in order to determine the influence of physical loads on the mental load subjective tool, through the NASA-TLX score.

According to DiDomenico and Nussbaum (2008), the Borg-CR10 and Borg-RPE are sensitive to physical activity, but they not affected by mental workload difficulty levels. However, both scales reflect the perceived exertion caused by physical activity. Borg-RPE is used to reflect physical load depending upon the subject's feelings, which relate to the strain and fatigue on muscles due to physical exertion. In addition, several studies have employed the RPE scale to assess physical workload and physiological stress incurred by, for example, a bicycle ergometer. The scale follows the physiologically linear increase in aerobic energy loads caused by increased physical demands (Borg, 1998). In contrast, the main feature of the CR10 scale is its reflection of the pain attribute that affects sensory perceptions due to high-intensity exercise. The result depends upon the subject's feelings of pain that occur due to the increase in physical demand. Moreover, the CR10 scale contains decimals below 0.5 between the anchors (i.e., 0.3) and uses 1.5 and 2.5 ratings in order to avoid bottom and ceiling effects and to make the scale more finely classified, so subjects can better describe their levels of pain and physical loads in too light physical load situations (Borg, 1998). However, both scores assess physical workloads, are simple methods, and are easy to understand. According to Borg (1998), both scales may be better used at high levels of physical intensity because each individual has a different physical workload capacity and, similarly, a different perception attribute about the physical loads. For example, some subjects select a score depending on their physiological state, while others evaluate their physical loads based on the pain that occurs due to their physical efforts. Pain is a very special attribute because most sensory perceptions merge into pain at the highest level of physical workload (Borg, 1998).

Therefore, this thesis used both scales to assess physical demands, with the aim of reducing the varying perception attributes of individuals toward physical exertion and helping participants to choose the appropriate scores for physical workload. In addition, previous papers have utilised both scales to evaluate physical activity load during multitasking situations to obtain the appropriate level of physical demand and to identify differences between levels of physical load changes (DiDomenico and Nussbaum, 2008; Fredericks et al., 2005). In summary, both scales were used because there are differences between individuals regarding physical workload judgments and, while some individuals evaluate physical load based on the range of effort that occurs due to physical activity, reflected by the RPE scale, others rate physical loads depending on the range of pain that occurs through physical activity, which is reflected by the CR10 scale. The creation process of the RPE scale depends on the assumption of increasing physiological stress associated with physical exercise (Borg, 1984). Furthermore, other study findings yield a high correlation between increasing levels of workload, HR, VO_2, and the Borg-RPE score, which are linear in shape (Borg, 1998). The Borg-CR10 scale was created for a similar purpose to the RPE scale, which was to evaluate the intensity of physical activity related to physiological functions. Like the RPE scale, the validity and reliability of CR10 have been proven in several studies. There is a high correlation between increasing levels of CR10 scores and increasing physical activity intensity on a bicycle as HR increases (Borg, 1984). The RPE and CR10 scales have been used in several studies to assess physical workload alterations, showing significant increases while physical load increased, for example, during the task of lifting boxes (DiDomenico and Nussbaum, 2008), cycling (Fredericks et al., 2005), and running on a treadmill (Borg, 1998). Thus, this study asked participants to complete both scale physical workload levels at each condition. For more details about the Borg scales, see the previous chapter, section 2.7.2.

3.3.3 General Materials and Apparatus

Most instruments were similar and used across all experiments; however, some additional materials were used in experiments 2 and 3. Thus, the details of these instruments are presented in this chapter to avoid repetition in the next chapters. All laboratory experiments were carried out in the Human Performance Laboratory

(HPL) in the School of Sport and Education, Brunel University. This laboratory contains all the apparatus used in the experiments, such as the stationary bicycle ergometer (see Figure 3.2a) that was used in experiments 1 and 2 in order to produce the physical workload dependent upon the maximum workload capacity for each participant. Two wooden boxes were used in experiment 3 with different loads in order to induce the physical workload (see Figure 3.2 b) dependent on participants' body weight, as stated previously in section 3.3.1 and Table 3.2. A Fujitsu-Siemens PC-compatible computer with a 19-inch monitor (resolution 1,024×768 pixels) was programmed to control the tone presentation; this computer also contained the MathsNet Mental Test 1.5 software, which was used to present the arithmetic tasks both visually and verbally (in a male voice); it was also used to present the spatial figures task. The details of mental tasks and physical tasks (stationary bicycle ergometer) are presented in each chapter of the experiments. See Figure 3.2a below.

Figure 3.2a Ergometer-bicycle and Fujitsu-Siemens PC

In addition, a Polar CS600 chest-electrode (CS600, Polar Electro Inc, Kempele, Finland) was used in order to measure heart rate (HR) and heart rate variability (HRV). Polar Pro-Trainer 5 software (5.35.164) was used to analyse HR and HRV and was used across all three experiments. Finometer (FMS, Finapres Medical Systems, Netherlands) was used to continuously record mean blood pressure and systolic blood pressure. Near-Infrared Spectroscopy (NIRS, SOMANETICS; 5100C) was used to measure regional tissue oxygenation (rSO2) to reflect the percentage of brain oxygenation changes, see Figure 3.2c. All the above-mentioned equipment was used across all experiments. The details of equipment for each experiment are stated in the relevant chapters.

Figure 3.2b Wooden boxes in experiment 3

Figure 3.2c Physiological equipment and NIRS

Besides the instruments already mentioned, additional instruments were used in experiments 2 and 3: pure tone and white noise were generated by the NCH tone software generator (ToneGen v.3 NCH Software Pty Ltd, Australia). The tone was generated at 2 kHz and was prerecorded and played back in the experiment. In addition, the high-pass filtered 2 kHz sound was fed through the WavePad Sound Master Editor (NCH) amplifier. The tone and white noise were presented for duration of 700 ms; six Logitech S-150 digital loudspeakers (20 kHz responses bandwidth) were used in the experiment to present the auditory workload. The speakers were placed in different locations; the details are illustrated later in Chapter 5, (section 5.2.1).

Experiments 2 and 3 were carried out in a chamber room (3.30m×3.0m×2.68m). In order to let the participants hear the tone stimulus at 2 kHz the level of sound in the room was weighted at approximately 33 dB (A) and to become more suitable to normal ear level. The intensity of the stimulus level was adjusted to 70 dB (A), which was measured by the CEM, DT-805 for a range of 35–130 dB on an A weighted scale for each speaker. The computer that generated the sound was connected to a CREST AUDIO CPX 900 amplifier (Crest Audio, Inc., USA) in order to support the translation process of tones from the computer to the speakers. This intensity was used to ensure that the participants heard the sounds clearly and to reduce the likelihood of error. The participants sat on the bicycle ergometer, which was placed in the centre of the room, while the speakers were placed on the perimeter of a 1.5 m radius circle around the ergometer.

3.3.4 Participant Sample Size

The total number of participants across all three laboratory experiments was the same. Each experiment involved a different sample of 30 participants (aged 25–35), 15 males and females for the physical workload vs. verbal mental task experiment and 15 males and females for the physical workload vs. spatial mental task experiment. The statistical description of all participants across all experiments is illustrated in Table 3.4. All participants were selected from Brunel University staff and students. This age range was selected as sufficient to give a homogenous group of participants and to detect one standard deviation difference between the mean for each dependent measure with α = 0.05 and power = 0.8. In addition, this reduced the differences between the subjects in age and physical ability.

Table 3.4 Statistical description of all participants' across all three experiments

Experiment No.	Total participants	physical workload vs. verbal mental task(Gender)	physical workload vs. spatial mental task (Gender)	Age range	Male (Mean ± SD)	Female (Mean ± SD)
1	30	15 (M=8,F=7)	15 (M=8,F=7)	25–35	(29.2±3.6)	(27.3±3.3)
2	30	15 (M=8,F=7)	15 (M=8,F=7)		(28.5± 2.2)	(30.7 ± 3.1)
3	30	15 (M=8,F=7)	15 (M=8,F=7)		(31.4± 4.2)	(28.1 ± 3.6)

The participants were healthy; this meant they had regular exercise every week, and none of the participants had any sort of back problems or had sustained any musculoskeletal injuries in the last 12 months. A healthy condition is important since, according to Borg (1998), there is a significant difference between the performance of healthy and unhealthy participants in physical exercises. Furthermore, none of them had participated in any kind of previous experiment. All participants were paid £25 for their time and effort. One important point to note in experiments 2 and 3 was that the participants completed the online version of the standard hearing test questionnaire (Self-Assessment of Communication, (Schow and Nerbonne, 1982)) so that their hearing health could be evaluated, since this test is used to check hearing normality (Coyne et al., 2001). The details of the participants involved in each experiment are given in the relevant chapters.

3.3.5 Experimental Procedures

There were substantial differences between the experimental procedures. Therefore, the procedures of each experiment are presented in the relevant chapters.

3.3.6 Data Analysis

The results of all three experimental studies underwent ANOVA repeated measures analysis to examine the impact of the physical workload and mental workload (verbal and spatial tasks) interaction on individual performance. As mentioned previously, the repeated measures analysis was used for the *within-subjects factor* (physical and mental workload) and *between-subject factors* (type of mental tasks and gender). In addition, the Shapiro-Wilk Test was applied to examine the data normality, and no considerable deviations were found, therefore permitting the use of parametric statistical analyses. Furthermore, the repeated contrast test and Tukey’s HSD test were used to determine the differences between levels of difficulty for both tasks, of interactions, types of mental tasks and gender differences. A 95% confidence level (i.e. $\alpha = 0.05$) was applied in the experiments. Furthermore, Pearson’s correlation (r) technique was used across all three experiments to determine the relationships between the objective and subjective variables.

3.4 SECOND PART: METHOD OF FIELD STUDY

As mentioned in section 3.1 and illustrated in Figure 3.1, one of the aims of this research was to validate the new model that resulted from the experimental studies. In order to validate the model, this thesis found a field job that required physical and mental effort from the operators to complete it. The aim of the field study was to validate and translate the experimental setting into a field setting. Prior to an explanation of the field study design, a summary of the background of the assembly task workload and performance is presented in the following section.

3.4.1 Assembly Task Workload

Many jobs involve cognitive functions and demands due to increasing technology, besides the manual loads in manufacturing and assembly of products (Mozrall and Drury, 1996). Assembling products is one of the common tasks in the industrial field that requires both types of workloads (Stoessel et al., 2008; Stork and Schubo, 2010). In addition to lifting parts for the assembly process and handling materials, operators must use their mental functions, including monitoring, perception, attention, and memory to complete the assembly tasks. In addition, the operator must use his/her cognitive functions in this type of task; perception ability is needed to recognise the stimulus and extraction characteristics (Stork and Schubo, 2010). Assembly work is very complex because it includes a number of variables to identify the difficulty of a task. In other words, the task includes many variables that need to be considered, such as the weight and size of assembly parts, the steps of the task, or instructions and time of the task (Stork and Schubo, 2010). The various allocations of visual attention, recalling the assembly steps information from memory concurrently with physical activities, could lead to mental bottlenecks (Stork et al., 2008). The operator needs to exert a high level of attention to detect any errors or mistakes in the assembly process and for the task instruction (Tang et al., 2003). Therefore, an increase in physical and mental workload interaction could increase errors and increase the time to complete the tasks.

It has been mentioned that the number of subcomponents increases time pressure in manual assembly tasks and leads to high mental workload beside the different levels of physical body movements (Stoessel et al., 2008), so performance may decrease. There are a number of factors that can impact on operator performance besides task workload, such as environmental factors, including noise and temperature stressors (Stoessel et al., 2008) and operator skill and experience (Stork and Schubo, 2010). They reported that skilled operators could perform multiple tasks perfectly and switch rapidly between tasks. It seems that physical and mental workloads in manual assembly tasks still exist, especially in assembly tasks that involve high physical activity as well as a cognitive load.

Therefore, the current thesis chose a truck assembly job in order to verify the model and to determine the impact of physical and mental workloads of assembly jobs on operator performance. In addition, the current field study produced a valuable recommendation in job design for this type of occupation. This study was carried out on truck assembly lines (Mercedes trucks assembly, Juffali Industrial Products Company in Saudi Arabia). This was selected to simulate the scenario of physical impact and mental activity tasks on operator performance. In addition, the factory is not fully automated; in other words, the operators need to perform physical activities and mental functions to complete their jobs. Therefore, the results will be valuable for improving the work system design in this factory and will aid technology in reducing overall workload and improving performance.

3.4.2 Field Study Design

The current study investigated the impact of the physical and mental workloads imposed by three different selected parts of assembly tasks in the Mercedes truck assembly line (side mirrors, front bumper, and side doors). The selection of these items depended upon the weight and size of the item, which reflected the physical workload; in contrast, the number of sub-component parts for each item assembly task reflected the mental workload. Therefore, this field study involved three different conditions of physical and mental workload assembly interactions. For example, the side mirror assembly was selected to reflect low physical lifting workload and low visual mental workload interactions, whereas the front bumper was designated as medium physical level because two workers lift the bumper manually. The side doors were identified as a high physical lifting workload because one operator lifts the door.

The details of these conditions and characteristics of each assembly item task are presented later, in Chapter 7 (see section 7.2.1).

3.4.3 Selection Output Measures

The data collection in this study depended on quantitative data observation methods (Bisantz and Drury, 2005). The data were collected directly from operators in their actual work setting. The output measures (dependent variables) were divided into three: first, the performance measure, which included accuracy, derived from checking each step in the production line and the time of task completion, which was determined by video recording. The time of each assembled item was compared with the standard time for each assembly item that was provided by factory management. The second variable was heart rate (HR) as a physiological indicator; however, measuring HR in a real situation can be affected by other factors such as environmental factors that increase the heart rate (Wickens and Holland, 2000). This research considered only heart rate, because it is difficult to record other physiological variables due to the difficulty of bringing instruments into the field. Third, the subjective assessment tools included NASA-TLX scores to measure mental workload (Hart and Staveland, 1988). In addition, the NASA-TLX is reliable to implement in the real domain to reflect the multitask workload (Baulk et al., 2007); the NASA-TLX measure used the total unweighted workload. In addition, perceived physical workload was evaluated using Borg-CR10 and Borg-RPE (Borg, 1982; Borg, 1998).

3.4.4 Materials and Apparatus

An LG laptop computer with a 17-inch monitor (resolution 1,024× 768 pixels) using the MathsNet Mental Test 1.5 software was used to present the arithmetic tasks visually. NASA-TLX score was used to assess assembly mental workload, and Borg's scales (RPE and CR10) were used to assess the physical loads. A Polar CS600 chest-electrode was used in order to measure HR. Polar Pro-Trainer 5 software (5.35.164) was used to analyse the heart rate. A digital camera was used to record the time taken by the operator to perform the task.

3.4.5 Participant Sample Size

Fifteen skilled male workers aged 25–35 with mean ± standard deviation (29.86 ± 3.12) were employed. In this study, all participants were male since there were no female workers in the Juffali Industrial Products factory; all such assembly jobs are performed by men in Saudi Arabia. All participants were healthy, and they completed the health questionnaire. Those selected to take part in the study gave their written, informed consent and were not paid for their participation other than their usual salary from Juffali. In addition, the entire sample was drawn from workers at this factory and was approved by factory management.

3.4.6 Field Study Procedure

At the beginning, the operators performed 5 minutes of arithmetic tasks at low, medium and high levels to evaluate sustained attention at the beginning of the shift and to obtain the NASA-TLX baseline evaluation and scores, and Borg's scores were evaluated (benchmarked) through the participants cycling on a stationary bicycle at three levels of difficulty (20%, 50% and 80% of W max). Also, the participants received an explanation of the measurements and the aims of the experiment. Noise levels were generally <80 dB in normal working conditions in the assembly factory. Temperatures ranged from 35°C to 40°C ambient heat. Then, the participants were asked to affix the chest electrodes for the heart rate monitor to their chests so the researcher could record the HR at baseline (rest) and continually during the work. The participants were asked to start the assembly task so that the times of the task and sub-tasks for each part were recorded. The number of errors for each part assembled were recorded by the checkpoint in the factory. This stage of checking was inspected for any mistakes or errors. The data were collected over 15 days with five participants for each part assembly (i.e. mirrors, bumpers, and doors), one participant per day. Each participant was asked to start assembling the mirrors task (two mirrors), so he started by lifting the first side mirror then putting it in the correct place. He kept lifting the mirror; then the other worker gave him the screws so he could attach the four screws for each mirror. The time was recorded for the task, and errors were recorded later in the inspection and checking point stage. The participant was then asked to complete the subjective assessment NASA-TLX. As mentioned before, the operators completed the three different levels of arithmetic tasks in order to calibrate the TLX score based on arithmetic task results, Borg-CR10 and Borg-RPE. On the second day, identical procedures were implemented for the second participant in the mirror assembly task. After completing the first five-participant group, the bumper assembly was performed. In this task, the participant first needed to lift the bumper with another participant; then the operators kept carrying it and fixed the six screws (four in the middle of the bumper and one screw on both sides of the bumper). The screws were given to the participant by his colleague. Then, the measures used followed the procedures used in mirror assembly.

A final group of five participants was observed completing the side-door assembly task (two doors). Each participant was required to load the door by himself and put it in the correct place. Other operators then supported him by giving him the screws; the participant had to keep the door in his hand and affix the seven screws; he then needed to balance the door, which was the last step. In this task, the participant had to balance both sides of the door. After the screws were affixed, the participant started to assemble the next door. HR was recorded continuously; after he finished the task, the participant was asked to complete the NASA-TLX, Borg-CR10, and Borg-RPE scores.

3.4.7 Data Analysis

The nonparametric test (Kruskal-Wallis Test) was used to determine the impacts of physical and mental workload interactions in the assembly job on the operators' performance, physiological variables, and subjective assessments tools, rather than the one-way ANOVA test (parametric test). The Mann-Whitney test was used alternatively to the independent t-test was implemented in order to determine the significant differences between the difficulty levels of assembly workload interaction, and the differences between the actual time of the task and the standard time (the theoretical value was obtained from factory data records) was obtained by means of the One Sample Wilcoxon (signed-rank) test. These nonparametric tests were applied as an alternative to parametric tests, as these tests were more appropriate to the data and a population for which it is difficult to assume a normal distribution, particularly in a field situation and with a small sample size (Field, 2009). Furthermore, according to Kolmogorov–Smirnov test the data was nonnormal. A 95% confidence level (i.e. $\alpha = 0.05$) was applied to these studies.

3.5 THESIS SEQUENCE

As mentioned previously in section 3.1, the thesis was conducted in three laboratory experiments and one field study. The aims and sequences of this research are illustrated in Figure 3.1. Chapter 4 contains the first experiment that investigates the impact of physical and mental workload interactions on visual attentional resources (verbal and spatial resources). The results provide an important contribution to the area of physical and mental workloads on visual verbal and spatial task performance. Chapter 5 describes the second experiment, which examines the effect of physical and mental workloads on auditory, verbal and spatial task performance. From both experiments' results, it was decided to change the physical workload from cycling to lifting boxes, since this task is more applicable to assembly and industrial jobs in the field, especially as the field study was applied in an assembly job that depends on lifting parts as physical loads. Therefore, Chapter 6 presents the third laboratory experiment, which examines the effect of a physical lifting and mental workload combination on auditory resources (verbal and spatial resources). Auditory resources were used in this experiment, since it was difficult to set up a physical lifting task concurrent with visual tasks. However, all the previous experiments' results were conducted to satisfy the main aim of the current research, which was to create a new theoretical model that understands the mechanisms of different levels of physical and mental workloads interaction with visual and auditory attentional resources.

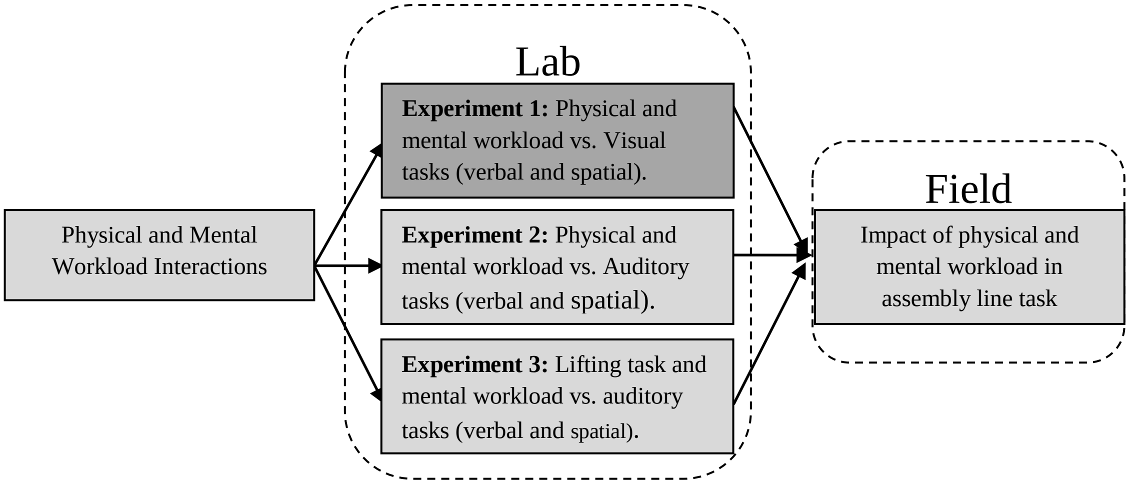
Chapter 7 presents a field study that was applied in order to validate and translate the findings that were derived from previous experiments into a field setting; the field study was implemented in a truck assembly factory, and investigated the impact of physical and mental loads in assembly tasks on operator performance under various conditions of difficulty. The integration of the experimental findings and the field study are illustrated in Chapter 8, and then the results were applied to identify the new model that clarified the contributions of physical and mental workloads on individual attentional resource performance. This study also identified valuable and worthwhile recommendations for designers; in particular, for the design of work-systems and machines in the assembly products job.

In conclusion, this chapter has presented the methodologies that were carried out in this thesis, in order to achieve the aim and objectives stated in Figure 3.1, namely that this research aims to understand the impact of physical and mental workload interactions on input dimensions in a multiple attentional resources model, using both visual and auditory resources and both dimensions' codes including verbal and spatial resources for each input dimension. Therefore, the three laboratory experiments were applied to achieve this main aim of the research and the experiments depended on quantitative data collecting, which included performance measures, physiological variables, brain activity measures and subjective assessment tools. To validate the new model derived from the experimental studies, the field study was implemented in an assembly job. This type of job was chosen since it requires physical and mental efforts concurrently from operators to complete it, and these efforts depend upon on the nature of the assembly products (e.g. size of the part and sub-components). Thus, this type of job is suitable as a real task to reflect the dual-task workload on performance. Also, in terms of results, the data collected in the field study were quantitative observations which involved performance, heart rate and rating scales measures. The results of this study provided worthwhile recommendations for assembly jobs; in particular, offering guidance for system design that helps to balance between task workload and operators' attentional resources.

4

CHAPTER 4 -Experiment 1:

EFFECT OF PHYSICAL AND MENTAL WORKLOAD INTERACTIONS ON VISUAL ATTENTIONAL RESOURCES PERFORMANCE



4.1 INTRODUCTION AND EXPERIMENTAL HYPOTHESES

For many years, researchers have been investigating the impact of task workload on individual performance (Tomporowski, 2003). Task workload may include physical activities and/or mental (cognitive) activities, and the impact of the demand governs operator performance. Two experiments in this chapter were conducted to evaluate the influence of different combinations of physical and mental workload on visual-verbal attentional resources and visual-spatial resources.

The relation between physical demands and visual cognitive task performance is an inverted-U (Reilly and Smith, 1986), the same as between mental workload and performance (Young and Stanton, 2002^{b}) aas stated in the literature review (Chapter 2), t. In particular, Reilly and Smith (1986) examined the effects of different physical demands (0, 25, 40, 55, 70, and 85% of VO2 max) on a visual psychomotor task (spatial task) and on a simple arithmetic task (verbal task). They found the performance of subjects was reduced at low and high levels of physical load whereas superior performance occurred at the moderate level (38% VO2 max). As mentioned in Chapter 2 (see section 2.6), most previous researchers have focused on examining different physical loads on one level of visual task (verbal or spatial). Therefore, the novelty in this experiment was investigating different physical and mental workload interactions on visual task performance. In addition, researchers have examined the effect of various mental workloads on visual task performance. For example, according to Young and Stanton (2002^{c}), different levels of mental workload relating to automation had an effect on driving performance and they concluded that the correlation between performance and mental workload is an inverted-U shape due to arousal level. Furthermore, Hwang et al. (2008) investigated the effects of different monitoring mental workloads in control room tasks on performance and they found a linear relationship between mental demands and performance. So, studies into the effects of physical and mental workload combinations are rare. According to Antunes et al. (2006), an medium level of physical activity leads to increasing arousal levels, up to a medium level, and the increased arousal supports visual attention and information processing, so task performance improves. Furthermore, physical workload can potentially support information processing through increasing the amount of oxygen available to the brain, since this will be depleted due to the increase in the level of mental effort (Perry et al., 2010). Therefore, this study assumes that participants perform best at a medium level of physical and visual mental workload interactions in both types of mental visual tasks (i.e., verbal and spatial tasks). In addition, a combined overload of physical and visual mental workload leads to worse performance due to a further increase in levels of physiological arousal. So, the hypotheses of a mechanism of physical and mental workload with both visual mental tasks are as follows:

- *The participants' best performance will occur at medium physical workload × medium visual mental (verbal and spatial) workload interactions.*
- *The participants' worst performance will occur with a high physical workload and high visual mental workload interactions due to the high level of arousal.*

According to Young and Stanton (2002^{a}), performance decreases with low a level of mental demand due to attentional resource shrinkage and low level of arousal, since the correlation between performance and arousal is curvilinear. In addition, the low physical exercise could leads to performance decrements in visual tasks due to low arousal level but this depend upon the type of mental tasks (Audiffren et al., 2008). On the other hand, according to Mozrall and Drury (1996), a moderate level of physical workload leads to an incremental increase in arousal level, so information processing in cognitive tasks improves, in particular, visual information processes. Therefore, the hypothesis for this experiment is that the medium level of physical workload fills the reduction in visual attentional resources, so performance at a medium level of physical workload and a low level of mental workload interaction will be superior.

- *Participants will perform better at medium physical workload × low visual mental (verbal and spatial) workload interactions due to an increased level of arousal caused by physical workload.*
- *Participants' performance will be worse with low physical workload × low visual mental workload interactions due to the low level of arousal.*

High-intensity levels of physical and mental workload combinations may lead to a reduction in the oxygen in the brain through more brain activation, since although a certain level of physical activity supplies the brain with more oxygen, to meet the amount of oxygen that is required to perform high-level mental demands (Antunes et al., 2006; Perrey et al., 2010), a high intensity physical workload increases the activation of muscles, which then need more oxygen, and that affects the amount available to the brain. Consequently, information processing becomes more difficult (Perrey et al., 2010). Kikukawa et al. (2008) found that increasing levels of visual demands in pilot tasks leads to high brain activation and blood oxygenation changes, which means that while activation of the brain increased, there was a reduction in available oxygen in the brain to meet the mental demand, and performance decreases. Therefore, the oxygenation change in the brain was measured with the NIRS technique, which measures frontal cortex oxygenation or regional cerebral oxygen saturation (rSO2). Thus, the hypotheses of this experiment are that the best participants' performance will occur at medium levels of physical and mental workload due to the medium physical exercise will translate more oxygen to the brain so, that will reduces the oxygen differences in the brain that occurs due to increase mental visual workload. In contrast, the high levels of mental and physical workload lead to a reduction in the amount of oxygen in the brain and a high percentage of oxygenation changes (i.e. high brain activation), so that will lead to worse performance.

- *The participants' best performance will occur with medium physical workload × low visual mental workload. Moreover, the participants' will perform better with a medium physical workload × medium visual mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.*
- *The participants' worst performance will occur with a high physical workload and high visual mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high visual workload since the increasing level of visual mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the visual workload.*

There are significant differences between males and females in some mental tasks (Halpern, 2000). Yagi et al.(1999) said that the the performance of females and males in simple visual cognitive tasks usually becomes the same while the subjects perfom tasks with some level of physical effort, since the low and moderated physical condition supports information processing through increasing level of arousal level, which in turn increase level of visual resource capcity and then leads to better perfromance in both genders, and differences disappear. In contrast, differences may occur when performance includes extensive physical activities, since there is a variation between the genders in physical strength and capacity (Borg, 1998). However, females perform better than males in visual-verbal tasks, whereas males excel in spatial tasks (Koscik et al., 2009), since men have an improved ability to process the orientation of spatial figures (Skrandies et al., 1999). Consequently, the hypothesis derived from this review is that there are no significant differences between males and females in visual mental tasks with low and medium workloads of physical and mental interactions since, the physical activity will increase the arousal level which in turn increase the attentional resources and facilitate the information process. In contrast, at the higher levels of interactions of workloads, female performance is expected to be better in visual-verbal tasks, whereas males are expected to outperform females in visual-spatial tasks.

- *No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level caused by the physical activity and increased oxygen delivered to the brain.*
- *At high levels of physical and mental workload combinations, men are expected to perform better than women in the visual-spatial task, whereas women will perform better in the visual-verbal task due to the physical workload capacity differences between the genders and the high level of arousal.*

4.2 STEP ONE – PILOT STUDIES

Two main pilot studies were implemented. The first pilot was conducted in order to validate the three mental demand levels (low, medium and high) of difficulty of the mental tasks: an arithmetic task (verbal task) and a spatial figures task (spatial task) that were used in this experiment. The second pilot study was conducted to validate the three difficulty levels of physical workload (low, medium and high) that were produced by the ergometer-bicycle.

4.2.1 First Pilot Study

The purpose of this study was to examine and validate the difficulty levels of the two visual mental tasks that were used in this experiment (arithmetic - verbal task and spatial figures - spatial task).

4.2.1.1 Design

This experiment was conducted to evaluate and validate the impact of three difficulty levels of mental workload for two tasks upon the attentional resources of operators: an arithmetic task (verbal) and a spatial figures task (spatial); the experiment was a full factorial repeated measures design. The three difficulty levels (low, medium and high) of both mental visual tasks are stated below. In the arithmetic task, three levels were selected similar to those used by Kakizaki (1987). A number of previous researchers have used arithmetic tests levels such as adding or subtracting two-digit random numbers, to reflect difficulty load on verbal resource information processing (Astin and Nussbaum, 2002; Fredericks et al., 2005; Skrandies et al., 1999).

The arithmetic mental task is considered to be a verbal task that places a load on working memory capacity, since individuals memorise the numbers as words in short-term memory (Halpern, 2000). Furthermore, Beilock (2008) stated that mental arithmetic problems place a higher demand on memory verbal resources than on spatial resources. Mathematical tasks include all the resources of working memory. For example, when an arithmetic task is displayed vertically, it relies on visuospatial attentional resources, since participants try to solve the problem in a spatial mental workspace. On the other hand, when an arithmetic problem is presented in a horizontal layout, the load is placed on verbal attentional resources since the participants memorise the arithmetic problem steps verbally (e.g. repeating the steps in their mind) (Beilock, 2008). Moreover, this type of arithmetic task can be classified as using verbal attentional resources since the subject needs to read the problem and then answer it in words.

- **The arithmetic mental task included the following three different levels:**

1. The low level involved addition/subtraction problems with numbers between 1 and 10.

2. The intermediate level involved addition/subtraction problems with two numbers between 3 and 35 for the subtraction operation and two numbers between 6 and 35 for the addition operation.

3. At the difficult level, participants were asked to complete high-level addition/subtraction problems with two numbers between 20 and 150 for the subtraction operation and between 20 and 150 for the addition operation.

For the first task, the MathsNet Mental Test 1.5 program (MathsNet, 2007 [www.mathsnet.net/form_mental.html]) generated different integer pairs under three different levels of difficulty (Figure 4.1). The test, which included 25 mental arithmetic problems, was set to last for five minutes. Participants were provided with on-screen feedback, including the number of correct responses that they provided, the percentage of correct responses, and the total time that elapsed during the specific condition period.

Figure 4.1 Screenshot of the mental math software

The spatial figures task used in this experiment was similar to that used in previous research by Koscik et al. (2009), who used three different levels of spatial figures. For example, the low level compared three figures with an original one, whereas the high level required participants to find the identical figure to the original one among nine figures. According to Halpern (2000), mental rotation is considered to be a spatial task that relies on spatial resources; numerous studies have measured the spatial reasoning abilities of individuals. Moreover, several studies have employed spatial figures such as mental rotation tasks in order to evaluate the load on the spatial ability resources of individuals (see, Peter and Battista, 2008). Therefore, the current study selected this spatial figures task with three different levels to reflect the impact of mental demands on spatial information processing (see below).

The Mental Rotation Program (Bjornson) was generated by Vienna Psychology Software (Vienna Test System model 64032; Psychological Testing, Lafayette Instrument, US). This program produces different shapes with various rotated angles at three levels of complexity (Figure. 4.2). The participants were asked to solve 25 problems with spatial figures for each condition level, and they were given five minutes to do so for each level. The program displayed on-screen feedback, including the number of correct responses provided, the average time required to complete each problem, and the total time elapsed.

- **The three levels of difficulty for the spatial figures mental task are:**

1. For the low level, participants were asked to find the identical figure to the original figure from a three-figure group.
2. At the intermediate level, participants were asked to select a figure identical to the original figure from six figures.
3. At the difficult level, participants were presented with nine figures and were asked to choose the identical figure to the original from the group.

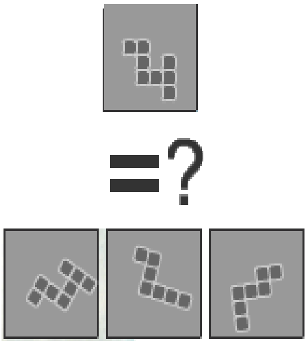


Figure 4.2 Screenshot of the spatial figures program

The experiments included two independent variables: an arithmetic task and a spatial figures task, each one conducted at three levels of difficulty. Furthermore, it contained three different dependent variables; namely: performance (accuracy and time of task); physiological indices (obtained by measuring the heart rate and heart rate variability); and subjective assessments of mental workload (observed by using the NASA-TLX scores) (Hart and Staveland, 1988).

4.2.1.2 Participants

Twelve participants (aged 25 –35), six males and six females, were selected randomly from Brunel University. The descriptive statistics for the participants are illustrated in Table 4.1.Participants were invited through an announcement issued on the University website. The study was approved by the Brunel University Ethics Committee (see Appendix C).

Table 4.1 Explanation statistics for sample size

	Male(n=6)		Female (n=6)	
Variable	Mean	SD	Mean	SD
Age (year)	28	2.7	27.8	2.9

4.2.1.3 Procedure

Participants were initially given a brief introduction to the experiment in order to familiarise them with the steps. They were then provided with instructions and advice on how to perform a mental arithmetic task and a spatial figures task. The participants' were selected the type of mental task (arithmetic and spatial figures tasks) randomly by the number generator software in order to consider the counterbalancing between both visual tasks.

Then, the participants were asked to affix the chest electrodes for the heart rate monitor to their chests, so that the researcher could record the HR and the HRV for each participant as they completed the assigned tasks. In addition, the height, weight, age, and gender of each participant was recorded and used to set up the heart rate monitor tool. The first experiment then began with the presentation of the mental arithmetic tasks. The participants were presented with different levels of difficulty randomly in order to reduce potential carry-over effects and fatigue. Each participant completed 25 questions at each level as accurately and quickly as possible in the allotted five minutes. The number of correct responses and the actual time required to complete the correct responses and the section were recorded by the software. The HR and HRV were recorded at rest level and continuously throughout the completion of each condition, using chest electrodes made by Polar (CS600, Polar Electro Inc, Kempele, Finland). Also, immediately after completing each trial, in the two to three minute break between each level, the participants were asked to complete the NASA-TLX scale. After completing the first experiment, i.e. three levels of arithmetic problems, the subjects were given five minutes to complete the NASA-TLX and rest.

Then, the second experiment (i.e. the spatial figures test) began. Participants were asked to continue wearing the chest electrodes for the HR monitor, so that the researchers could continue measuring HR and HRV. The Mental Rotation Program generated different figures with various angles of rotation at three different levels (i.e. low, medium, and high). The program also recorded the number of correct choices and the time required to complete the task. Each condition included 25 problems, and participants were given 5 minutes to complete each level. In addition, they took 2 to 3 minutes to rest and complete the NASA-TLX.

4.2.1.4 Results

Performance

Participant performance was measured by recording the accuracy and time of the arithmetic and spatial figures tasks (i.e., the mental rotation test). In addition, the responses were related to the task-difficulty levels for each task (Figure 4.3). Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity met for both accuracy and time of task (p>0.05).

Accuracy and Time of Task (Total cumulative time of task)

In this section the percentage of correct responses (accuracy) of participants and the cumulative time of task for both tasks (arithmetic and spatial figures tasks) were analysed. Generally, accuracy and speed were related to the task difficulty workloads.

The ANOVA showed that the levels of difficulty of the arithmetic mental task and spatial figures tasks had a significant impact on participants' accuracy ($F(2,22) = 40.91$, $p<0.01$). However, the effect of workloads interactions on accuracy was not significant ($F(2,22) = 1.21$, $p=0.231$).Moreover, the repeated contrast analysis showed a significant difference was observed between the medium and the high workload of the arithmetic test ($p<0.01$), as well as a difference between the low and medium workloads ($p<0.01$). In addition, participants were observed to have higher accuracy in arithmetic tasks than spatial figures tasks at all three workloads.

The effect of task type on accuracy was significant ($F(1,11) = 9.12$, $p<0.05$). However, the Tukey HSD test showed significant differences between the arithmetic and spatial figures tasks at low and medium mental workloads ($p<0.01$) and ($p<0.01$) whereas, there was no significant difference at the high workload ($p=0.084$). In addition, when the task level (arithmetic and spatial figures) increased, the accuracy decreased (Figure 4.3).

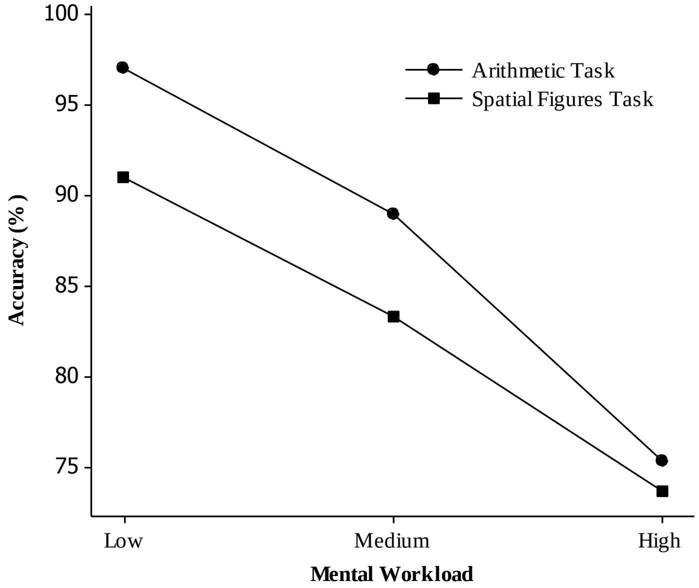


Figure 4.3 Response accuracy implies correlation the three levels of mental workload for both arithmetic and spatial figures tasks

In terms of task time, the repeated-measures ANOVA indicated that the tasks workloads had a significant impact on participants' speed (*F* (2,22) = 606.46, $p<0.01$), and when the task difficulty increased, the speed significantly decreased, as shown in Figure 4.4. Moreover, a repeated contrast test revealed a significant difference between the medium workload and the high workload of the arithmetic test ($p<0.01$); also the difference between the low and medium workloads was significant ($p<0.01$). However, no significant impact from task type interaction and their workloads on time was observed (*F* (2,22) = 0.92, $p=0.81$).

The effect of task type on time was significant (*F*(1,11) = 12.37, $p<0.05$). In addition, spatial figures tasks consumed more time than arithmetic tasks at medium and high workloads. A Tukey HSD analysis presented significant differences between the arithmetic and spatial figures tasks at medium and high workloads ($p<0.05$ and $p<0.05$), whereas there was no significant difference at the low workload ($p=0.122$).

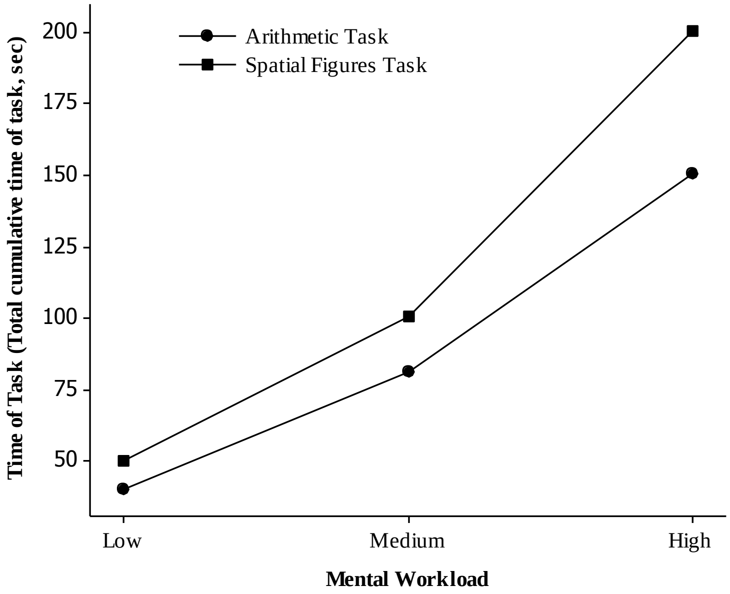


Figure 4.4 Cumulative time of task (sec) implies correlation the three levels of mental workload for both arithmetic and spatial figures tasks

Physiological Parameters

The HR and HRV parameters were measured in order to determine the impact of mental demand on the arousal level of the participants. As in previous research, a correlation was observed between these parameters and the workload and difficulty of the task. Table 4.2 presents the mean HR for participants as they completed the low-level, medium-workload, and high-workload mental tasks (i.e., both the arithmetic and spatial figures tasks). The table reveals that, on average, participants' HR rose as the difficulty level of the task increased. However, according to Mauchly's test, both HR and HRV were not met the assumption of sphericity ($p<0.05$).

Table 4.2 Heart rate observation (beats/min) mean and standard deviations across all participants

	Low level		Medium level		High level	
	Mean	SD	Mean	SD	Mean	SD
Arithmetic Task	72.8	8.6	78.3	9.6	86.2	9.2
Spatial Figures Task	81.8	8.7	88.6	10	96.6	8.97

However, the repeated measures ANOVA indicated a significant effect of task type (i.e. arithmetic and spatial figures) on HR, ($F(1,11) = 30.28$, $p<0.01$). Also, the data analysis indicated that a significant impact was made by both tasks workloads on participants' HR ($F(1.3,14.8) = 50.07$, $p<0.01$), and when the task difficulty increased, HR significantly increased, as shown in Figure 4.5. On the other hand, no significant impact from task type interaction and their workloads on HR was observed (*F*(1.4,14.9) = 0.224, *p*=0.775). According to repeated contrast comparisons, the mean HR increased significantly during participants' completion of the high-workload arithmetic task (*p*<0.01) compared to the medium workload. Also, the HRs of participants rose significantly (*p*<0.01) during their completion of the medium workload arithmetic task versus that of the low-workload arithmetic task.

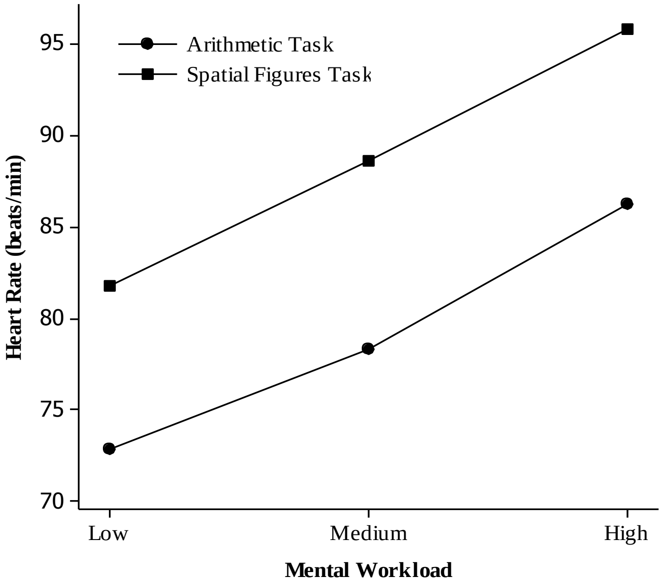


Figure 4.5 Heart rate (HR) implies correlation the three levels of mental workload for both arithmetic and spatial figures mental tasks

Table 4.3 presents the mean HRV for the low, medium and high workloads mental tasks (i.e. both the arithmetic and spatial figures tasks). As presented in the table, the mean HRV decreased based on the difficulty of the task because when the task workload increased, the HRV dropped.

Table 4.3 Heart rate variability observation (ms) mean and standard deviations across all participants

	Low level		medium level		High level	
	Mean	SD	Mean	SD	Mean	SD
Arithmetic Task	746.2	82.7	640.3	73.7	595.1	80.7
Spatial Figures Task	696.6	77.4	621.2	70.5	574.9	78.8

ANOVA analysis indicated that the task type (i.e. arithmetic versus spatial figures tasks) significantly affected the mean HRV (*F*(1,11) = 8.93, *p*<0.05). Also, the data analysis indicated that the task workloads of the arithmetic and spatial figures tasks significantly impacted participants' HRV (*F*(1.3,13.8) = 38.14, *p*<0.01); i.e., when the arithmetic and spatial figures task difficulty workload increased, HRV significantly decreased, as shown in Figure 4.6. A Tukey HSD analysis indicated that there was a significant difference between the arithmetic and spatial figures tasks at low, medium and high workloads (*p*< 0.05). However, there was no significant impact of task type interaction on HRV (*F*(1.3,14.7) = 0.884, *p*=0.386).

Contrast comparisons indicated that there was a significant difference between the low and medium workloads (*p*<0.01) and, a significant difference was also observed between the medium and high workloads (*p*<0.01).

Moreover, contrast comparisons indicated that the HRV decreased significantly when participants completed the high-workload spatial figures task compared to the medium workload (*p*<0.01). Also, the mean HRV dropped significantly (*p*<0.01) when participants completed the medium workload spatial figures task, versus that of the low-workload spatial figures task.

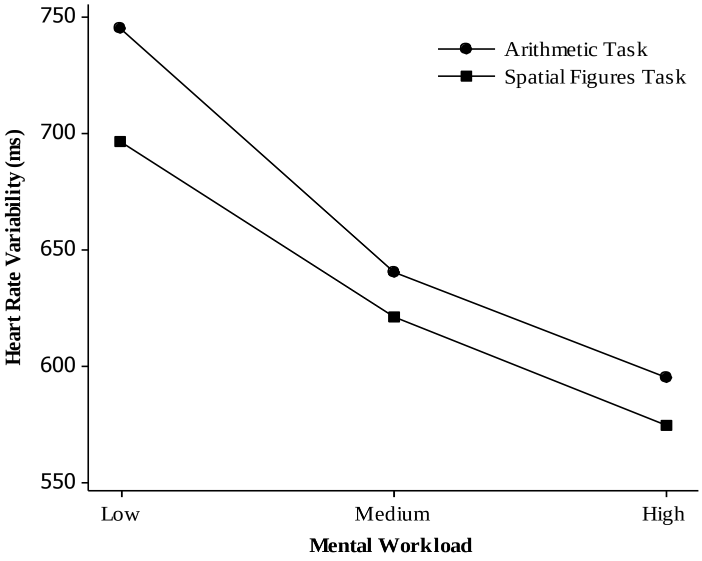


Figure 4.6 Heart rate variability (HRV) implies correlation the three levels of mental workload for both arithmetic and spatial figures mental tasks

NASA-TLX Score

Mauchly's test illustrated that the TLX variable met the assumption of sphericity ($p>0.05$). ANOVA analysis indicated that both mental tasks' workloads significantly impacted participants' overall TLX score ($F(2,22) = 245.24$, $p<0.01$) (see Figure 4.7). As the arithmetic task-difficulty increased, the overall NASA-TLX scores increased ($p<0.01$ from low to medium; $p<0.01$ from medium to high). In addition, the overall workload from the NASA-TLX increased when the spatial task workload became more difficult (low to medium workload, $p<0.01$; medium to high workload, $p<0.01$). However, the overall NASA-TLX scores were significantly related to the scores on the mental demand dimension for both the arithmetic and spatial figures tasks ($r= 0.99$, $p<0.01$ and $r=0.99$, $p<0.001$, respectively). However, no significant impact of task type interaction and their workloads on TLX score was seen ($F(2,22) = 1.07$., $p=0.17$).

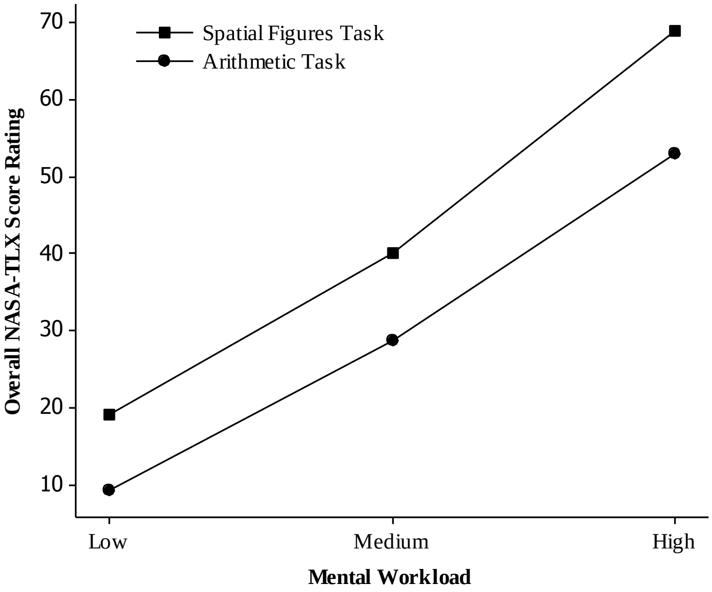


Figure 4.7 Mean overall NASA-TLX ratings implies correlation mental tasks workload

ANOVA analysis indicated that task type (i.e., arithmetic versus spatial figures tasks) significantly affected the mean TLX score ($F(1,11) = 18.11$, $p<0.05$). Spatial figures tasks were observed to have a higher score than arithmetic tasks at all three workloads of difficulty. A Tukey HSD analysis showed that there was a significant difference between arithmetic and spatial figures at a low workload (p<0.05), medium (p<0.05) and high workload (p<0.05).

4.2.1.5 Discussion

The accuracy and time of task indicated that the arithmetic and spatial figures task workloads were varied in difficulty, as expected. In addition, it showed that the manipulation of mental workload of the tasks was validated from low to high workload level. Moreover, participants' accuracy responses decreased in sequence as the mental demand from the arithmetic and spatial figures tasks increased. These findings are similar to those of previous research studies. DiDomenico and Nussbaum (2008) found that performance decreased with increasing mathematical operation load. With regard to mental workload (i.e., arithmetic tasks), Hwang et al (2008) pointed out that an increase in monitoring and arithmetic processing demand led to a degradation in individual performance. Generally, the spatial figures task was shown to be more difficult than the arithmetic task (verbal task), because the participants achieved a higher workload of accuracy in the arithmetic task than the spatial task. This is consistent with Peters and Battista (2008), who said that spatial tasks, which depend on spatial resources, are more difficult than verbal tasks for participants.

Finally, the analysis of participants' performance for both of the visual mental tasks showed that there was a significant difference between the low and medium workloads, as well as between the workload and high workloads. In addition, the cumulative time of task in both tasks was significantly different between the low and medium workloads, and between the medium and high workloads.

Physiological indices in this study were affected by the mental workloads of the tasks (i.e., both arithmetic and spatial figures tasks). The physiological data analysis found a significant difference between the tasks, which appears to indicate that participants found the spatial task to be more difficult than the arithmetic task. That difference may be reduced by increasing the difficulty level of the arithmetic task, but this would produce a potential problem in the validation of these levels by pilot study. However, both tasks had a significant impact on physiological parameters, and these effects were parallel; therefore, this would not affect the study. However, the participants' HR parameter was positively related to the arithmetic and spatial task difficulty workloads. Specifically, as the arithmetic task level increased, the HR also increased and, similarly, the HR increased as the workload of the spatial figures tasks increased. This was consistent with previous experimental studies by Fredericks et al., (2005) and Hwang et al., (2008) who found that participants' HR was affected by the complexity levels of the mental workload in the form of arithmetic and monitoring tasks.

The study results indicated that a significant relationship exists between the subjective mental assessment tool (i.e., the NASA-TLX) ratings and the arithmetic and spatial figures task workloads. Specifically, the NASA-TLX score increased with the increase in task workload for both types of tasks. In general, the experimental data analysis indicated that the NASA-TLX scores were sensitive to changes in mental workloads. This finding is similar to that of numerous papers. For example, DiDomenico and Nussbaum (2008) and Hwang et al. (2008) concluded that increases in NASA-TLX ratings were related to an increase in mental workload. For most participants, the highest NASA-TLX rating was recorded after completing the most high workload arithmetic and spatial figures tasks. On the other hand, the lowest score was recorded after completing the low workload of both tasks. However, the interaction between gender and task workloads did not significantly impact the NASA-TLX scores.

4.2.1.6 Conclusion

In conclusion, the workloads of difficulty of the arithmetic and spatial figures tasks were validated, which was the target of this experiment. Indeed, all of the variables (performance, physiological variables, and NASA-TLX scores) that were measured in this study indicated that the design of both tasks achieved three intensity workloads (low, medium, and high) of mental effort. Furthermore, the participants' incorrect answers, HR, and NASA-TLX ratings increased when the arithmetic and spatial figures workloads increased. In contrast, the HRV of the participants correlated negatively with the complexity workload for both tasks; in other words, the HRV declined as the arithmetic and spatial task workloads increased. The results showed significant differences between the spatial figures and arithmetic tasks in performance, physiological variables and TLX score. The spatial figures task was more difficult than the arithmetic task, since it took more time and fewer correct answers were given than with the arithmetic task. There were significant differences between both tasks in time at medium and high workloads of difficulty. However, there were no interaction effects between the tasks, so that will not impact on the study. Based on the findings of this study, each of these tasks appears to include three cognitive load conditions that are demanding enough to produce reliable differences. Therefore, both tasks appear suitable to use in the research study.

4.2.2 Second Pilot Study

This experiment was conducted to evaluate and validate the impact of three difficulty levels of physical workload. The experiment was a full factorial repeated measures design. Three workloads of the physical task were developed to simulate physical workload. These physical workload levels were selected in order to satisfy the three difficulty levels of physical demands, from low- to high-intensity workload, and the design of these physical workloads was derived from previous research. This technique has frequently been implemented by other researchers to investigate the impact of different physical workloads on task performance (e.g. Arcelin et al., 1998; Hogervorst et al., 1996; Lulofs et al., 1981). The physical workload levels depend on the maximum workload capacity (Wmax) of each participant (Hogervorst et al., 1996). The bicycle-ergometer technique (Monark 874-E) was used to create the physical demand (Figure 4.8). This instrument uses different loadings to produce different levels of physical difficulty. Also, it displays the workload in Watts related to weight and velocity (rpm). This task included performing physical actions by pedalling (leg movements) on the bicycle-ergometer with different resistance (pedal loads) in terms of constant speed (rpm) and duration (min). The three levels were:

- **Low workload** involved 20% of maximum workload capacity (Wmax).
- **Medium workload** involved 50% of Wmax and,
- **High workload** involved 80% of Wmax

Figure 4.8 Bicycle-ergometer

4.2.2.1 Materials

All performance trials were conducted using a bicycle-ergometer (Monark 874-E). A Poalr CS600 (CS600, Polar Electro Inc, Kempele, Finland) chest-electrode was used in order to measure heart rate (HR). Polar ProTrainer 5 software (5.35.164) was used to analyse the heart rate and heart rate variability. A Finometer-B12365 was used to record the blood pressure (BP) continuously. In addition, Borg-CR10 and RPE Scores (Borg, 1998) were used to evaluate the physical workload of each task.

4.2.2.2 Participants

Four healthy participants with experience in cycling (2 male and 2 female; aged 25 – 35) were invited through an announcement issued on the Brunel University. They completed a health questionnaire (see Appendix B) and they presented with good health and no back injury in the previous 12 months. The statistics for the participants are illustrated in Table 4.4. The task procedures were explained to all participants. Participants were invited to participate through the University website. The experiments met the ethical rules of the School of Engineering and Design at Brunel University (see Appendix C)

Table 4.4 Explanation statistics for sample size

	Male(n=2)		Female (n=2)	
Variable	Mean	SD	Mean	SD
Age (year)	30	1.8	28	1.4
Height (cm)	175	2.4	167.5	2.1
Weight (kg)	80.5	3.5	54.5	2.1
*Wmax (Watt)	210	7.1	182	4.2

***Wmax is the maximum workload capacity in Watt.**

4.2.2.3 Procedure

At the beginning, the participants were given a brief introduction about the experiment in order to familiarise them with the steps. Also, the participants were provided with instructions and advice on how to perform the cycling task. Then, the participants were asked to affix the chest electrodes for the heart rate monitor to their chest and Finometer-B12365 such that we could record the HR and the BP, respectively for each participant, as they completed the assigned tasks. In addition, the height, weight, age, and gender of each participant was recorded and used to set up the heart rate monitor and Finometer (136-sv) tools.

On the first visit, each participant completed an incremental maximal test of maximum workload capacity (Wmax). They performed 6 minutes of cycling at 60 W, and then during the 6 minute duration, the workload was increased by 30W every minute until exhaustion (heart rate reached 160 beats/min and speed dropped to under 60 rpm) in order to determine the maximum workload capacity for each person. Before that, heart rate (HR) and blood pressure (BP) at rest level were measured, as well as the height and weight. However, the HR and BP were recorded continuously during the test. Then, on the second visit, the participants were asked to complete three different conditions of physical workload (20, 50 and 80% of maximum workload capacity). The conditions were selected randomly in order to counterbalance fatigue effects. The participants were asked to continue wearing the chest electrodes for the HR monitor so that the researchers could continue measuring HR and BP was measured continuously with the Finometer-B12365 in each trial. The participants were given six minutes to complete each condition. In addition, they took approximately five minutes to rest (until HR reached to rest-level) and complete the Borg-CR10 and RPE scores.

4.2.2.4 Results

Physiological Parameters

The HR and BP parameters were measured in order to determine the impact of the physical demand on the physiological state. As in previous research, a correlation was observed between these parameters and the level of difficulty of the physical task.

ANOVA analysis indicated a significant increase in heart rate (*p*<0.01) and mean blood pressure (*p*<0.01) as the physical pedalling resistance increased (physical workload). In addition, a Tukey HSD test showed there were significant differences between low level vs. medium level and medium level vs. high level in both variables, HR and BP (*p*<0.05). Figure 4.9 illustrates that the mean HR for participants increased significantly when the physical load increased. Moreover, the mean blood pressure for both males and females increased significantly as the difficulty of the cycling task increased (Figure 4.10).

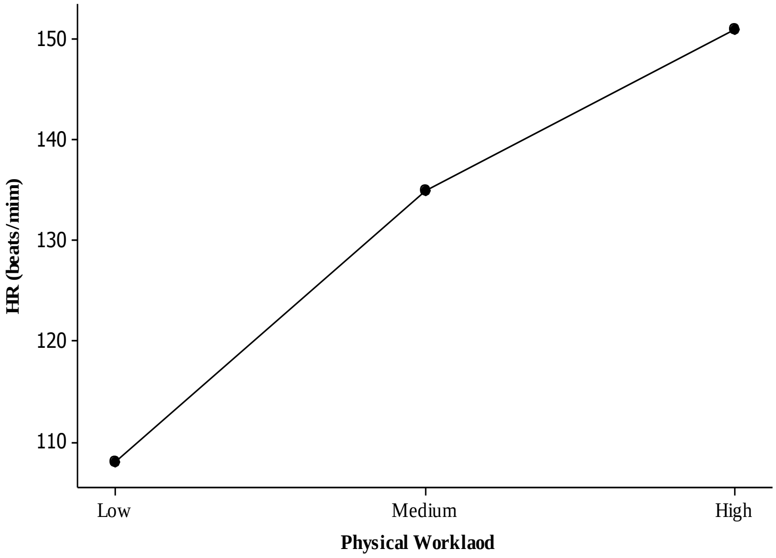


Figure 4.9 Heart rate (HR) implies correlation with the three levels of physical workload

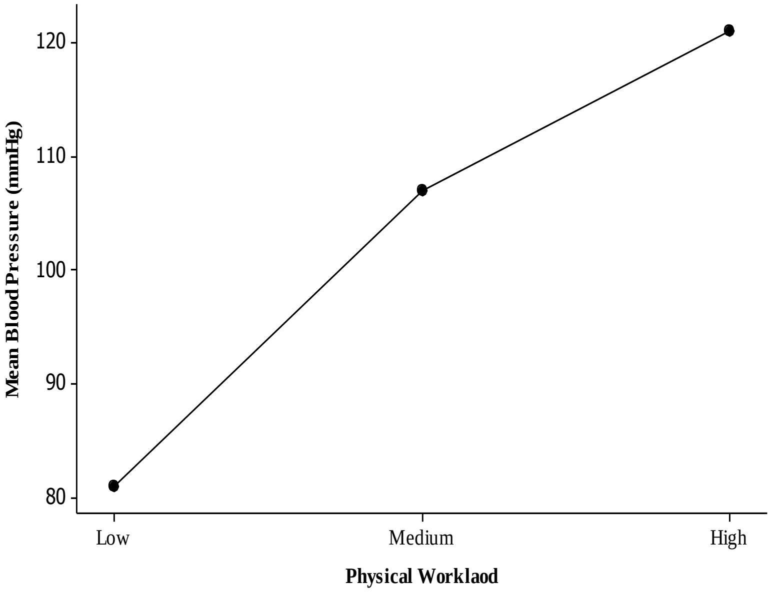


Figure 4.10 Blood Pressure (BP) against the three levels of physical workload

Borg-CR10 and RPE Assessments Tools

The mean Borg-CR10 and RPE scores for the assessments completed after finishing each of the low, medium, and high workloads of physical task show an increase based on the level of difficulty; i.e. when the physical task workload increased, both Borg-CR10 and RPE ratings also increased significantly ($p < 0.01$) (Figure 4.11 and Figure 4.12). According to a Tukey HSD test there were significant differences between low level vs. medium level ($p<0.05$) and medium level vs. high level ($p<0.05$).

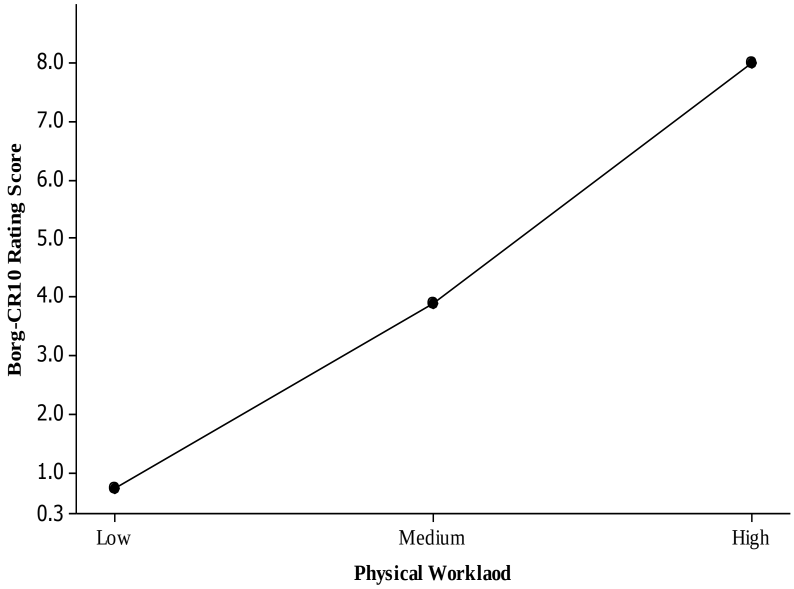


Figure 4.11 Mean Borg-CR10 ratings against three levels of physical task

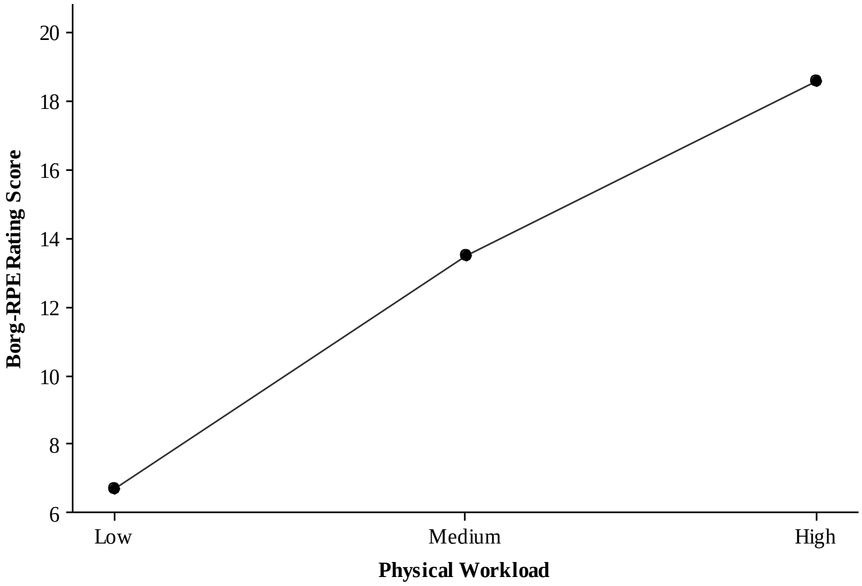


Figure 4.12 Mean Borg-RPE ratings implies correlation the three physical workload

4.2.2.5 Discussion and Conclusion

This pilot study was carried out to verify and validate three levels of physical workloads (20, 50 and 80 % of maximum workload capacity), selected for low, medium and high respectively. The three workloads of physical load were verified and validated. Physiological (HR and BP) and subjective Borg scores (CR10 and RPE) were significantly impacted by the physical workloads that were selected and showed that the physical levels selected varied in their perceived difficulty. Both HR and BP were lower at the low level of physical task, since both increased significantly as the physical workload increased. Both physiological measures presented a significant difference between low and medium workloads and medium level vs. high workload of physical demands, as with the Borg ratings. This was similar to previous research that showed significant differences between mean HR across three workloads of difficulty (Hogervorst et al., 1996). Lulofs et al. (1981) found that the RPE significantly increased as pedalling resistance load increased (20, 50, 70, 80 and 90% max workload capacity). In addition, the subjective Borg-CR10 and RPE assessment tool scores increased when the difficulty of the task increased. The scores significantly increased between low and medium and between medium and high workloads. These results were consistent with Borg’s (1998) findings. Borg stated that increasing physical exercise loads lead to an increase in heart rate and blood pressure. Furthermore, he found that the RPE and CR10 rating scores significantly increased with an increase in pedalling resistance in cycling from 100 Watt to 150 Watt. Therefore, this pilot study verified and validated the fact that the three workloads of physical workloads (20%, 50% and 80% of maximum workload capacity) produced different difficulty workloads from low to high intensity.

4.3 MAIN STUDY METHOD

4.3.1 Experimental Design

The current study involves two experiments to investigate the effect of the interaction of physical workload (PWL) and mental workload (MWL) on individual attentional resources in the performance of visual-verbal (arithmetic) and visual-spatial (figures) tasks. The experiment was a 3×3 full factorial repeated measures design. Table 4.5

illustrates the nine conditions of interaction between the physical and mental arithmetic tasks and spatial figures tasks. Repeated measures analysis was used for the *within-subjects factor* (three physical and mental workload levels of interactions) and *between-subjects factor* (type of visual mental tasks (i.e. verbal and spatial tasks) as well as gender, as mentioned in Chapter 3 (see section 3.3.1).

Table 4.5 The nine conditions of interaction, physical load and mental workload, of both visual tasks (arithmetic and spatial figures)

		Mental Visual Arithmetic Workload *OR* Spatial Figures Workload (MWL)		
		Low Mental Workload	Medium Mental Workload	High Mental Workload
Physical Workload (PWL)	Low load (20% Wmax)	Participants' performance will be worse	Participants' performance will be worse	Participants' performance will be worse
	Medium load (50% Wmax)	Participants' performance will be better	Best performance will occur under this condition	Participants' performance will be worse
	High load (80% Wmax)	Participants' performance will be worse	Participants' performance will be worse	Worst performance will occur under this condition

4.3.2 Experimental Tasks

- ***Mental Arithmetic Task (Visual mental verbal task)***

The MathsNet Mental Test 1.5 program (MathsNet,2007 [www.mathsnet.net/form_mental.html]) for the first task generated different integer pairs under the three different levels of difficulty. The details and levels of this task were validated previously in pilot study section 4.2.1.

- ***Mental Spatial Figures Task (Visual mental spatial task)***

The Mental Rotation Program (Bjornson) was generated by Vienna Psychology Software (Vienna Test System model 64032; Psychological Testing, Lafayette Instrument, US) and was used to produce spatial tasks using the Shepherd system. This programme produces different shapes with various rotated angles under three levels of complexity. The details and levels of this task were mentioned and validated previously in the pilot study section 4.2.1.

- ***Physical Task***

The bicycle-ergometer technique (Monark 874-E) was used to create the physical demand (see Figure 4.8 in section 4.2.2). The details and levels of this task were mentioned and validated previously in the pilot study section 4.2.2.

4.3.3 Outcome Measures

As mentioned in Chapter 3 (see section 3.3.2), all outcome measures (i.e. dependent variables) were similar across all experimental studies. There were four main outcome measures (dependent variables): Performance (accuracy and response time), physiological measures (HR, HRV [RR interval, ms] and mean BP), and rSO2 (oxygenation changes in the brain) and subjective assessment tools (NASA-TLX, Borg-CR10 and Borg-RPE). Furthermore, the mental demand dimension (MD) and physical demand dimension (PD) in NASA-TLX analyses were presented as mentioned in Chapter 3 (see section 3.3.2).

4.3.4 Participants

Two groups of fifteen participants, both male and female and aged between 25 and 35, participated in the experiment. The first 15 subjects participated in the first experiment, physical workload vs. visual-verbal mental task. The statistical description of male and female participant groups across the experiment is illustrated in Table 4.6. The statistics of physiological measures for the participants are illustrated in Table 4.7. The other 15 participants participated in the second experiment, physical workload vs. visual-spatial mental task (See details in Chapter 3 section 3.2.5.) The study was approved by the Brunel University Ethics Committee (see Appendix C).

Table 4.6 Statistical explanation of participants' and age

Total participant	physical workload vs. verbal mental task(Gender)	physical workload vs. spatial mental task (Gender)	Age range	Male (Mean ± SD)	Female (Mean ± SD)
30	15 (M=8,F=7)	15 (M=8,F=7)	25 – 35	(29.2±3.6)	(27.3±3.3)

Table 4.7 Anthropometric and physiological characteristics for sample size in both visual tasks (Mean±SD)

	Arithmetic(n=15)	**Spatial Figures Task(n=15)**
Variable	***Mean± SD***	***Mean± SD***
Age (years)	29.2±3.6	27.3±3.3
Height (cm)	176.3±6.3	167.7±4.4
Weight (kg)	78.5±7.0	63.1±5.7
HR at rest level (bpm)	77.83 ±5.83	75.20±7.22
MBP at rest (mmHg)	88.18 ±4.73	83.95 ±7.39
rSO2 at rest level (%)	65.9 ±7.69	64.6 ±4.75
Wmax (Watt)*	271 ±29.8	205.0±21.9

*Wmax: is the maximum workload capacity.

4.3.5 Materials and Equipment

Most of the equipment and materials used across all experiments were similar; details of the equipment used in this chapter were presented in the previous chapter (see Chapter 3, section 3.3.3).

4.3.6 Procedure

Physical Workload vs. Visual Arithmetic Mental Task

At the beginning, the participants were given a brief introduction to the experiment in order to familiarise them with the steps, and they were given the participant information sheet (see Appendix C) and informed consent form (see Appendix F). All instruments used in this experiment were presented in Chapter 3 (section 3.3.3). The participants were provided with instructions and advice on how to perform the cycling task and the mental arithmetic task. The participants were asked to affix the chest electrodes for the heart rate monitor onto their chests so that the researchers could record HR at baseline (rest) and during the trial. The participants visited the laboratory twice. In the first session they were asked to do incremental exercise tests until exhaustion on the bicycle-ergometer under constant speed (60 rpm), with a 6min duration warm-up at 60 W, in order to determine the maximum workload capacity (Wmax) of each participant. Additionally, the workload rose every one minute by 25 W, until the heart rate reached 160 beats/min and the pedalling rate decreased below 60 rpm (H). The equation below:

$$\mathbf{Wmax = Wout + (t/150) * 25} \quad (1)$$

Equation (1) (Hogervorst et al., 1996), was used to calculate the maximal workload capacity, where Wout is the workload of the last trial part in Watts, t is the time of last trial in seconds and 150 is time in seconds and 25 is workload in Watts.

On the second visit, participants were provided with instructions and advice on how to perform the cycling task and the mental arithmetic task. After that, the participants were asked to affix the chest electrodes for the heart rate monitor on their chests so that the HR and the HRV for each participant could be recorded as they completed the assigned tasks. Before that, the height, weight, age, and gender of each participant were recorded and used to set up the heart rate monitor tool. Additionally, the NIRS was fixed on the front of the head of the participants to measure the oxygenation (rSO2) of the brain. Blood pressure was recorded continually during the task. The first experiment was started and the condition was selected randomly in order to reduce potential carryover effects and fatigue. Each participant completed three task trials under various conditions and each condition was of six minutes duration. When the participant started pedalling, presentation of the mental arithmetic tasks (e.g. 34 + 56 =?) began concurrently. The participant responded by pressing the answer on the number keyboard on the front of the bicycle. Also, each participant completed 25 questions within each level as accurately and quickly as possible within the allotted six minutes. The number of correct responses and the actual time required to complete the section was recorded directly by the software.

After each trial, the participant rested for five minutes until their heart rate reached resting level. Also, immediately after completing each trial, the participants were asked to complete the NASA-TLX scale (see Appendix G) and the Borg-CR10 and RPE scales (see Appendix H) during the rest period between each level.

Physical Workload vs. Visual Spatial Figures Task

The second experiment (spatial figures task) included two visits and was essentially identical to the previous experiment. The first visit evaluated the maximum workload capacity for each participant (see previous experiment procedures). In the second visit the participants were provided with instructions and advice on how to perform the cycling task and the spatial figures mental task. All physiological equipment was fixed as before, and the experiment was started. The participants started cycling and the figures were presented. The participant responded by choosing a figure through a keyboard placed on the front of the bicycle. After each trial, the participant rested for five minutes until their heart rate reached resting level. Also, each participant completed 25 questions within each level as accurately and quickly as possible in the allotted six minutes. The number of correct responses and the actual time required to complete the section was recorded directly by the software. Also, immediately after completing each trial, the participants were asked to complete the NASA-TLX scale (see Appendix G) and the Borg-CR10 and RPE scales (see Appendix H) during the rest period between each level.

4.4 RESULTS

In order to satisfy the hypotheses the results and determine the impacts of different physical and mental workloads interactions on visual mental tasks (arithmetic and spatial figures tasks) performances as well as gender differences were divided into four parts that included: Performance analysis, physiological variables, brain activity analysis (rSO2, regional cerebral oxygen saturation) and subjective assessments tools. The descriptive statistics (mean ± standard deviation) for all measures (accuracy, time of task, HR, HRV, MBP, rSO2, Borg-CR10, Borg-RPE and NASA-TLX scores) across all nine physical and mental workload interaction conditions are illustrated in Appendix I.

4.4.1 Performance

Participants' performance was measured by recording the accuracy and time of task (cumulative time). Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for both accuracy and time of task ($p<0.05$), so the F-adjusted was used.

Accuracy

The ANOVA technique showed that the difficulty levels of physical ($F(1.8,49.2) = 84.81$, $p<0.01$) and mental workload ($F(1.91,51.5) = 57.21$, $p<0.01$) have a significant impact on participants' accuracy in both visual mental tasks. The interaction effect of physical × mental workload on accuracy was also significant

(*F*(2.7,70.9) = 11.16, $p<0.05$). When the difficulty levels (arithmetic and spatial figures) were increased, accuracy decreased. Unexpectedly, better accuracy was observed at medium levels of workload interactions, but it was not the best. Interestingly, findings showed that the participants performed better at a low physical level (20% Wmax) × low and medium mental workloads in both visual tasks; also, they outperformed in accuracy at a medium physical load (50% of Wmax) × low mental level in both visual tasks, as did low physical workload (Figure 4.13). Thus, the low and medium physical workloads facilitated information processing, leading to better accuracy at a low mental level of visual mental tasks, arithmetic, and spatial figures due to increased level of arousal and additional oxygen delivered to the brain. Furthermore, the worst accuracy was observed with high physical (80% of Wmax) and mental workload interactions in both visual tasks.

According to the contrast analysis, a significant difference was observed between all levels of physical workload ($p<0.05$), except between low physical and medium physical loads at low mental demands in both arithmetic and spatial figures, which was not significant ($p=0.057$ and $p=0.066$ respectively). In contrast, there was a significant difference between low and medium levels of mental workload ($p<0.05$), except between low physical and medium physical loads at low mental demands in both arithmetic and spatial figures, which was not significant ($p=0.057$ and $p=0.066$ respectively). In contrast, there was a significant difference between low and medium level mental workloads ($p<0.05$) at medium and high physical demands except, the differences between low and medium mental workloads at low physical load in both arithmetic and spatial figures tasks was not significant ($p=0.034$ and $p=0.031$), respectively. The difference between medium and high levels was significant ($p<0.01$). Additionally, the analysis presented a significant difference between mental workload levels, low level vs. medium level and medium level vs. high level ($p<0.01$) in both mental tasks. The analysis showed the impact of task type factor was not significant (*F*(1,26) = 1.38, $p=0.172$).

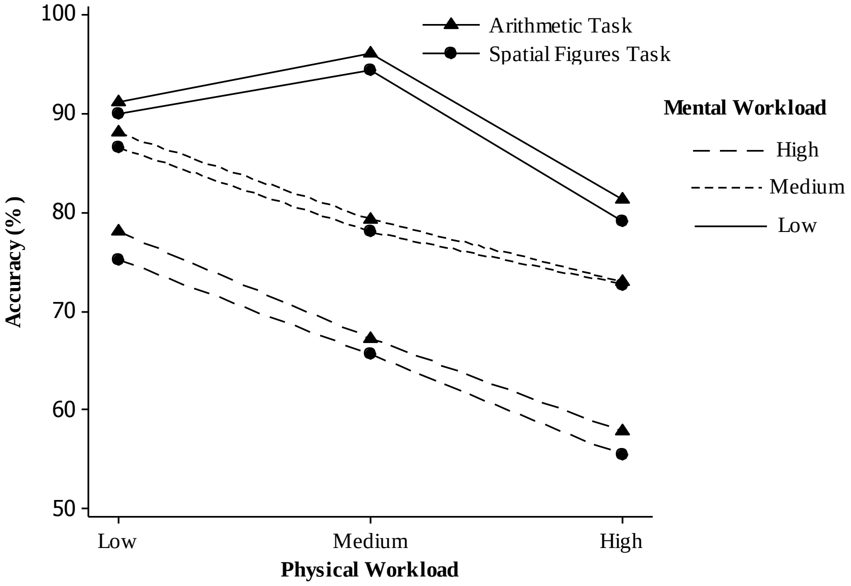


Figure 4.13 Mean accuracy of spatial figures and mental arithmetic visual tasks responses against physical and mental workload interactions

Time of Task (Total Cumulative Time of Task)

The ANOVA technique showed that the mental workload factor significantly influenced the participants' cumulative time ($F(1.6,42.5) = 1243.12$, $p<0.01$) and the physical workload factor significantly impacted on participants' time ($F(1.8,49.8) = 606.74$, $p<0.01$). Moreover, The interaction effect of physical × mental workload time of task were significant ($F(2.9,74.7) = 54.52$, $p<0.05$). The results showed that, as hypothesised, the medium level of physical workload (50% Wmax) leaded to better total time of task at low and medium workloads of both visual mental workloads (i.e., spatial figures and arithmetic) but not the best. As expected, response time at low workload of mental and physical (20% Wmax) interactions was greater than the time at a medium physical load and low mental load, but these differences were not significant. Moreover, a medium level of physical workload leaded to the better time of task in both mental tasks at a medium workload. Furthermore, the worst time of task observed with high physical and mental workload interactions in both visual tasks. Generally, when the task levels (arithmetic and spatial figures) and physical workload increased, the time of task increased (Figure 4.14).

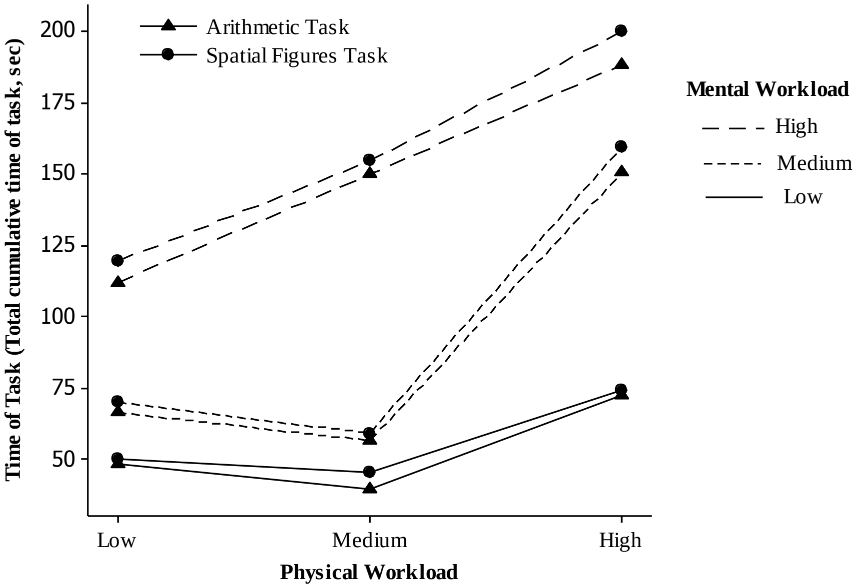


Figure 4.14 Cumulative time of task on arithmetic and spatial figures mental tasks against physical and mental workload interaction

According to the contrast analysis, a significant difference was observed between all levels of physical workload, except between low and medium physical loads at a low mental workload in the arithmetic and spatial figures tasks (*p*=0.082 and *p*=0.052, respectively) and between low and medium physical loads at a medium mental demand workload in both mental tasks conditions (*p*=0.058 and *p*=0.062, respectively). Therefore, low physical (20% Wmax) and low mental workload interactions lead to quicker performance in visual tasks. The medium physical level (50% Wmax) also leads to better task times in both tasks at a low mental workload. However, the analysis presented a significant difference between mental workload levels, low workload vs. medium workload, and medium workload vs. high workload in the arithmetic and spatial figures tasks (*p*<0.05 and *p*<0.01, respectively). The difference between medium and low mental workloads was not significant at a low physical workload in the arithmetic and spatial figures tasks (*p*=0.054 and *p*=0.061, respectively). In addition, the difference between medium and low mental levels was not significant at a medium physical workload in the arithmetic and spatial figures tasks (*p*=0.072 and *p*=0.082, respectively). The analysis showed that the impact of task type was not significant (*F*(1,26) = 0.91, *p*=0.092).

Gender Differences and Performance (Accuracy and Time of task)

The results showed that the effects of gender on accuracy ($F(1,26) = 1.33$, $p=0.211$) were not significant. In addition, the influence of gender on time of task was not significant ($F(1,26) = 2.07$, $p=0.287$).

4.4.2 Physiological Parameters

Objective measurement parameters were used to assess physical workload, mental workload, and workload interactions. In addition, they were used to reflect physiological arousal due to the physical and mental workload effect. The measurements used were physiological indicators that included HR, HRV, and mean BP; brain activity was measured by rSO2. Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for HR, HRV, and MBP parameters ($p<0.05$), so the F-adjusted was used; it met for the rSO2 measure ($p>0.05$).

Heart Rate (HR)

Mental workload had a significant impact on participants' HR ($F(1.7,46.7) = 724.99$, $p<0.01$) in both tasks. Furthermore, physical workload levels in both visual tasks (arithmetic and spatial figures) significantly affected participants' HR ($F(1.5,41.5) = 1054.80$, $p<0.01$). This showed that physiological arousal was increased due to increased workload levels. The effect of the physical × mental workload interaction on HR was significant ($F(2.1,55.6) = 42.36$, $p<0.05$). Generally, mean HR significantly increased as physical and mental workload increased (Figure 4.15). The Tukey HSD post-hoc analysis revealed that a high level of mental workload (spatial figures task) versus medium and high physical loads gave a higher HR ($p<0.05$ for both).

However, repeated contrast analysis showed a significant difference between all levels of physical workloads levels ($p<0.05$), except between medium and high physical workloads at a high mental workload in the arithmetic task ($p=0.069$). Also, the analysis showed a significant difference between all levels of mental workload ($p<0.05$), except between medium and high mental loads at high physical workload in the arithmetic task (*p*=0.081). The impact of task type (arithmetic and spatial figures tasks) was not significant on HR (*F*(1,26) = 1.89, *p*=0.132).

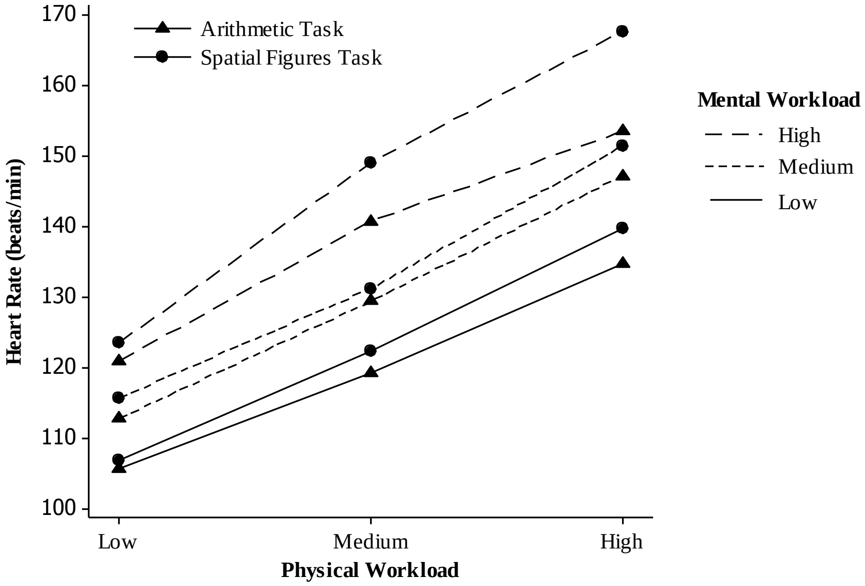


Figure 4.15 Mean of heart rate for arithmetic and spatial figures mental tasks against physical and mental workload interaction

Heart Rate Variability (HRV)

The ANOVA showed that mental workload significantly influenced participants' heart rate variability (HRV) (*F*(1.6,42.5) = 96.07, *p*<0.01). In addition, the physical workload factor had a significant impact on participants' HRV (*F*(1.8,49.5) = 101.97, *p*<0.01). Moreover, the effect of the physical × mental workload interaction on HRV was significant (*F*(2.5,65.2) = 37.81, *p*<0.05). In addition, when the mental task workload increased (arithmetic and spatial) participants' HRV decreased, whereas when the physical workload increased, HRV increased (Figure 4.16).

The repeated contrast analysis illustrated that there was a significant difference between the low and medium levels of physical workload and medium vs. high levels of physical workload in both tasks (*p*<0.05), except that there was no significant difference between HRV at medium and high physical versus medium and high mental workload interactions in the spatial figures task (*p*=0.072 and *p*=0.084 respectively). Additionally, there was a significant difference between mental workload levels under all conditions in both the arithmetic and spatial figures tasks

($p<0.05$), except between low and medium mental levels versus low physical workload interactions in both visual tasks ($p=0.088$ and $p=0.073$ respectively).

The impact of the task type factor was significant on HRV ($F(1,26) = 13.92$, $p<0.05$). However, Tukey's analysis showed that there were significant differences between the arithmetic and spatial figures tasks at high physical load vs. medium mental demand ($p<0.05$) and between high physical load vs. high mental demand ($p<0.05$), whereas there was no significant difference between both tasks under other interaction conditions (see Figure 4.16). Generally, HRV values were lower in the spatial figures task condition than the arithmetic task. That means the spatial figures task interaction with physical workload was more complex than the arithmetic task performed concurrently with physical activity.

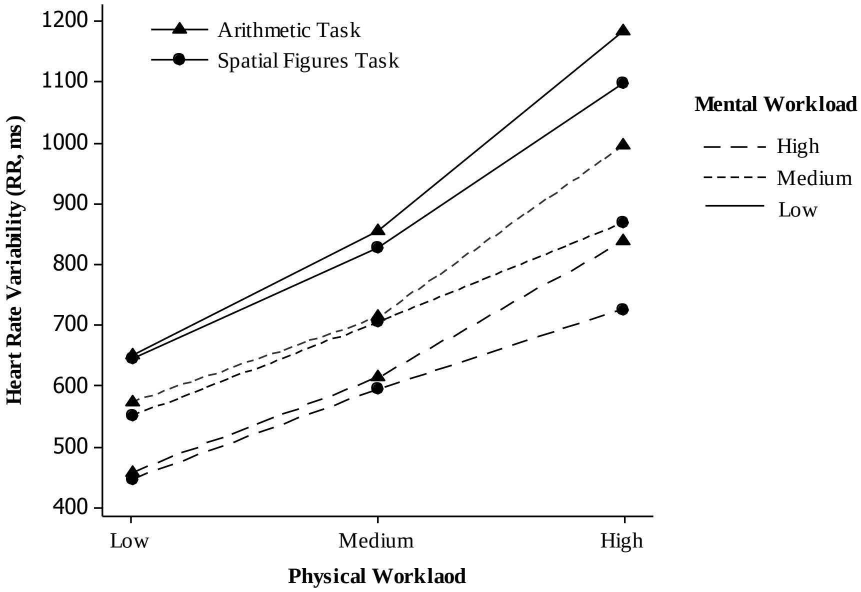


Figure 4.16 Mean of heart rate variability of arithmetic and spatial figures mental tasks against physical and mental workload interaction

Mean Blood Pressure (MBP)

The ANOVA showed that mental workload significantly influenced participants' mean blood pressure (MBP) ($F(1.8,47.2) = 260.33$, $p<0.01$). In addition, the physical workload factor significantly impacted on participants' MBP ($F(1.9,49.4) = 670.24$, $p<0.01$). Moreover, the effects of physical and mental workload interaction on BP were significant ($F(3.2,82.8) = 4.82$, $p<0.05$). In addition, when the task workloads (arithmetic and spatial) and physical workload increased, the average blood pressure also increased (Figure 4.17). Tukey's HSD post-hoc analysis indicated that at high levels of mental workload versus medium and high physical loads, the spatial figures task showed higher MBP (*p*<0.05 for both), as well as at a medium physical load versus medium mental load (*p*<0.05).

According to repeated contrast tests, there were significant differences between the low versus medium physical levels and medium versus high physical levels under all conditions of workload interaction (*p*<0.05). In addition, there were significant differences between the low mental load versus medium level and medium mental level versus high level under all conditions of workload interactions (*p*<0.05). The impact of the task type factor was not significant (*F*(1,26) = 1.33, *p*=0.089).

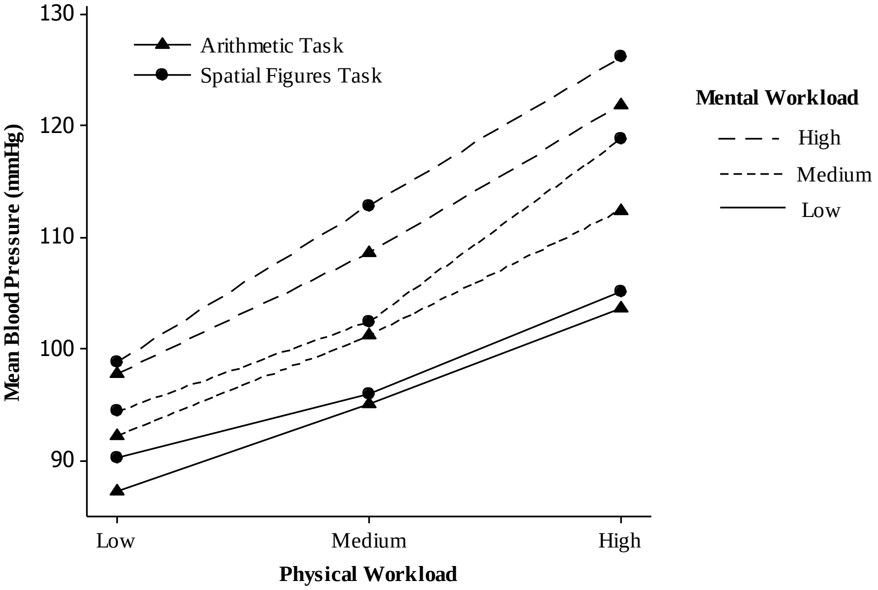


Figure 4.17 Mean blood pressure of arithmetic and spatial figures mental tasks against physical and mental workload interaction

Gender Differences and Physiological Parameters

In the gender analysis, an ANOVA showed that the gender variable was significant on HR (*F*(1,26) = 10.87, *p*<0.05). Furthermore, Tukey's analysis showed no significant differences in HR between males and females in visual arithmetic tasks under all levels of workload interactions (*p*>0.05). In contrast, there was a significant difference between genders in the spatial figures task at high levels of physical workload (80% Wmax) × low mental level (*p*<0.05), high level of physical workload

× medium mental level ($p<0.05$), and high level of physical workload × high mental level ($p<0.05$), since female HR values were higher than those for males under these levels of workload interactions in the spatial figures task. (See Figure 4.18).

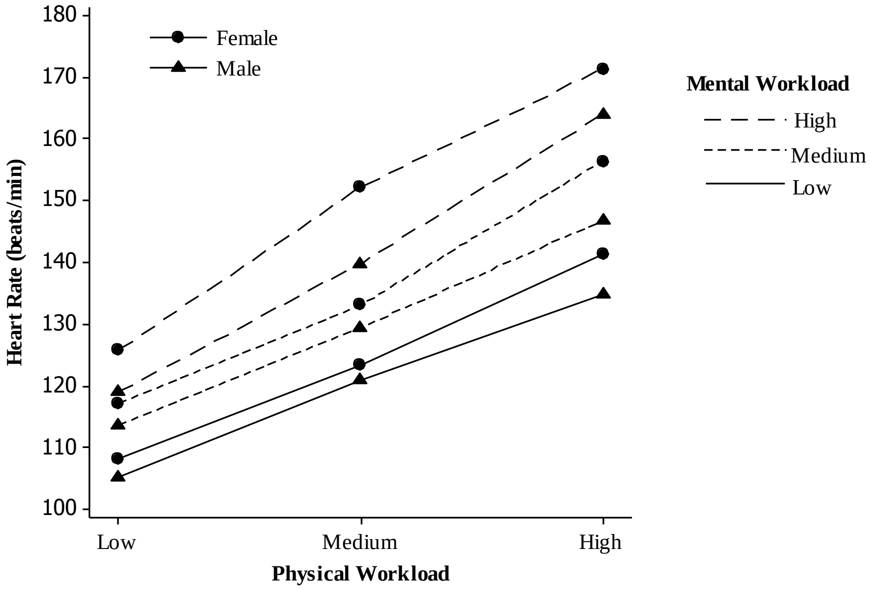


Figure 4.18 Mean HR for both genders against physical and mental workload interactions in spatial figures task

However, ANOVA analysis found that the gender factor was not significant on HRVs ($F(1,26) = 0.11$, $p=0.14$).

The ANOVA showed that effects of gender on MBP were significant ($F(1,26) = 11.73$, $p<0.05$). The mean female MBP was greater than male under all conditions in both arithmetic and spatial figures mental tasks. However, the Tukey HSD test showed that there were no significant differences between males and females in the arithmetic task ($p>0.05$). In contrast, differences between genders in MBP occurred during the spatial figures task condition at high levels of workload interactions. In particular, a high level of physical workload (80% Wmax) × low spatial figures mental level ($p<0.05$), high level of physical workload × medium mental level ($p<0.05$), high level of physical workload × high mental level ($p<0.05$) and medium level of physical workload (50% Wmax) × high mental level ($p<0.05$). See Figure 4.19.

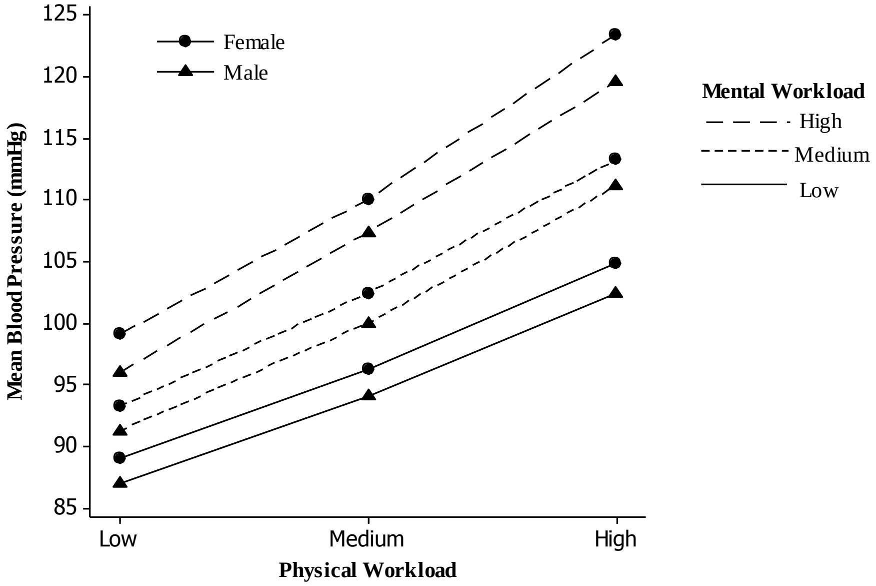


Figure 4.19 Mean blood pressure for males and females in the spatial figures task during physical and mental workload interactions

4.4.3 Brain Activity versus Physical and Mental Workload Interactions

Regional Cerebral Oxygen Saturation (rSO2)

As expected, the ANOVA showed that mental workload significantly influenced the participants' percentage of blood oxygenation in the frontal cortex of the brain (rSO2) ($F(2,52) = 153.86$, $p<0.01$). In addition, the physical workload factor significantly impacted on the percentage of oxygenation ($F(2,52) = 59.82$, $p<0.05$). Moreover, the effect of physical and mental workload interactions on rSO2 was significant ($F(4,104) = 15.89$, $p<0.05$). However, the percentage of oxygenation in the brain increased when both mental tasks levels (arithmetic and spatial) increased, whereas it decreased when the physical workload increased (Figure 4.20). Tukey's HSD analysis indicated that the spatial figures task showed a higher rSO2 mean than the arithmetic task at a high mental workload vs. the three physical loads levels ($p<0.05$).

According to contrast tests, there was a significant difference in rSO2% between low physical (20% Wmax) and medium level (50% Wmax) in all conditions in both mental tasks ($p<0.05$). The difference between medium physical load and high physical load (80%Wmax) was not significant at medium and high levels of mental workload ($p=0.09$ and $p=0.12$, respectively). The significant differences between rSO2 at three levels of mental workload ($p<0.05$) and at all levels of interactions in both mental tasks is shown in Figure 4.20. The impact of task type factor on rSO2% was not significant ($F(1,26) = 3.21$, p=0.098).

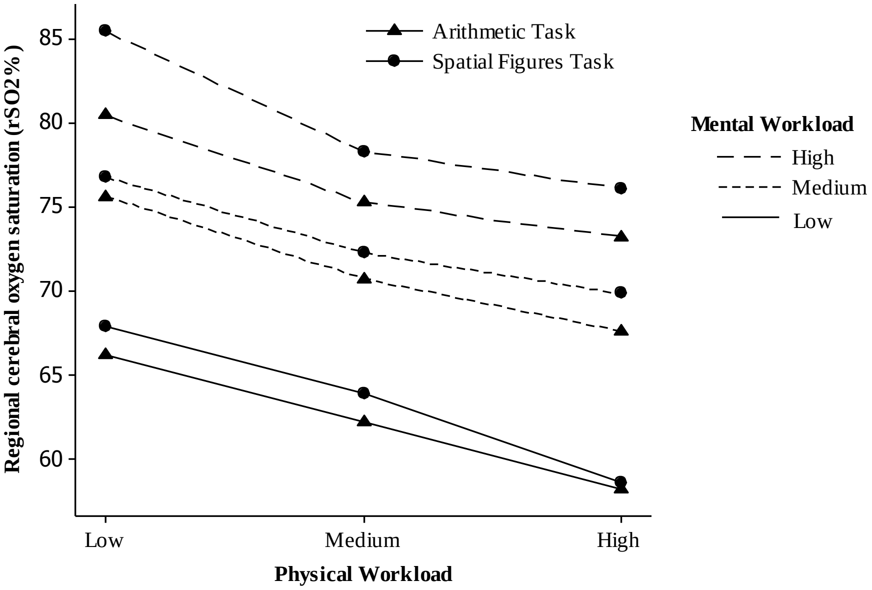


Figure 4.20 Mean cerebral oxygen saturation percentage (rSO2) during performance arithmetic and spatial figures tasks – physical and mental workload interactions

Gender Differences and rSO2

In the gender analysis, the ANOVA showed that the gender variable was not significant ($F(1,26) = 3.12$, p=0.083).

4.4.4 Subjective Assessment Tools

Mauchly's test was used to check the assumption of sphericity. The test illustrated that the assumption of sphericity was not met for Borg's scales (CR10 and RPE) and the NASA-TLX scale ($p<0.05$), so the F-adjusted was used.

Physical Workload Assessment Tools

Perceived physical workload was assessed by the Borg CR10 Scale and RPE scales. The effect of physical workload on the Borg-CR10 and RPE was significant ($F(1.94,50.4) = 718.15$, $p<0.01$ and $F(1.7,44.2) = 729.11$, $p<0.01$, respectively). In contrast, the effect of visual mental workload on Borg's scores was not significant (Borg-CR10, $F(1.9,49.5) = 1.53$, p=0.227 and RPE, ($F(1.3,33.6) = 0.085$, p=0.80) (Figure 4.21 and Figure 4.22). However, according to contrast tests, there was a significant difference between the physical workload levels in both scores under all levels of workload interactions (*p*<0.01). ANOVA analysis showed that the effect of task type factor on Borg scores CR10 and RPE were not significant (*F*(1,26) = 1.83, *p*=.93) and (*F*(1,26) = 2.31, *p*=0.87, respectively).

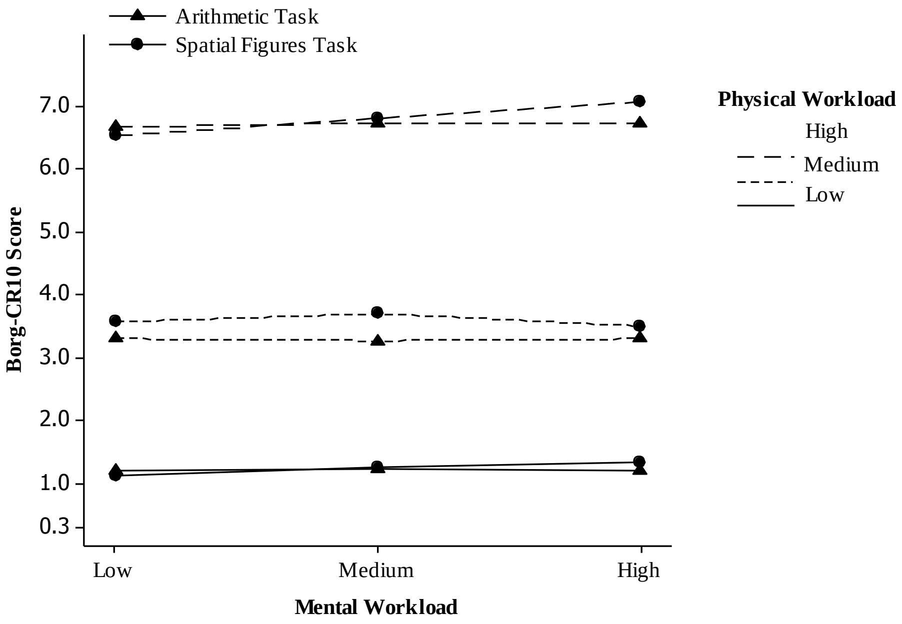


Figure 4.21 Borg-CR10 scores for arithmetic and spatial figures mental tasks against physical and mental workload interaction

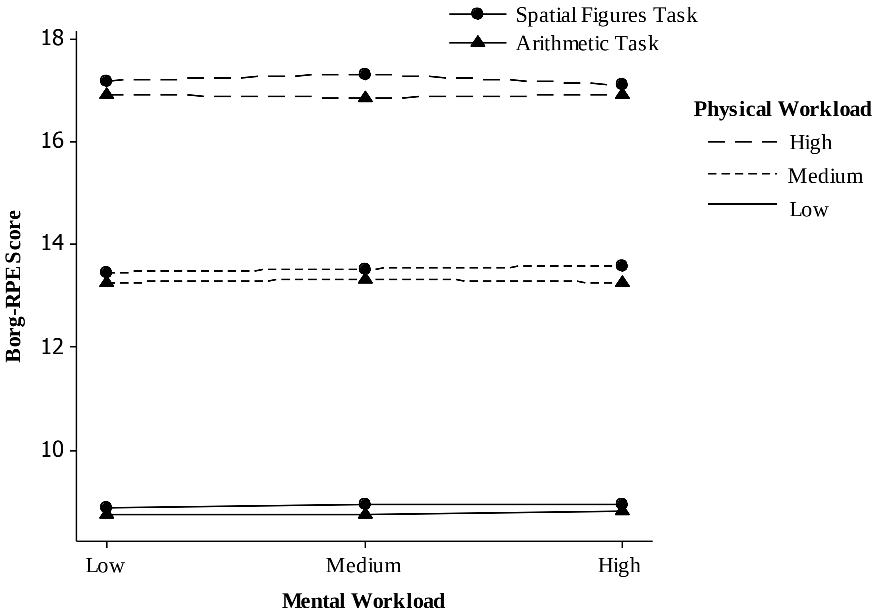


Figure 4.22 Borg RPE scores for arithmetic and spatial figures mental tasks against physical and mental workload interaction

NASA-TLX Assessment Tool

Subjective workload was measured by NASA-TLX ratings. Overall workload ratings on the TLX were calculated by averaging all the dimensions of the NASA-TLX ratings, as shown in Equation (3), below. The ratings (R) are for the six dimensions, as the TLX was included in the physical dimension.

$$\text{NASA-TLX Rating} = (RMD + RPD + RTD + ROP + RFR + REF)/6 \quad (3)$$

The mental workload factor highly significantly influenced the NASA-TLX scores ($F(1.8,46.7) = 2614.45$, $p<0.01$). In addition, the physical workload factor significantly impacted the ratings ($F(1.7,44.5) = 1539.34$, $p<0.01$). However, the effects of the physical and mental workload interaction factors on NASA-TLX were not significant ($F(3.5,90.6) = 2.84$, $p=0.25$). In addition, when the task levels (arithmetic and spatial) and physical workload increased, the NASA-TLX rating also increased. (Figure 4.23).

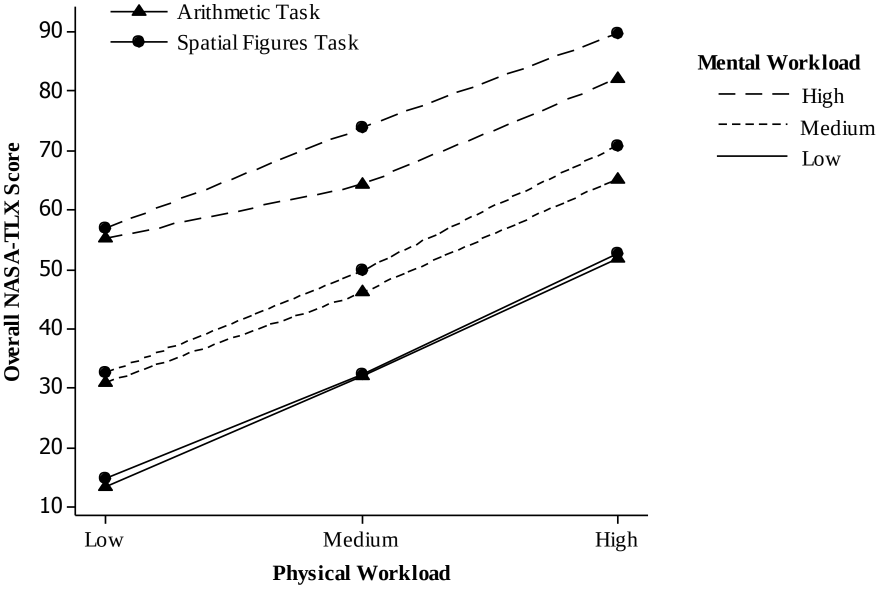


Figure 4.23 Overall NASA-TLX score implies correlation with physical and mental workload interactions for arithmetic and spatial figures tasks

Contrast analyses showed that there were significant differences between the three levels (low, medium, and high) of each physical workload, in interacting with mental workload in both mental task conditions ($p<0.05$); moreover, the differences were observed between mental workload levels ($p<0.05$). The impact of task type on overall TLX score was not significant ($F(1,26) = 1.63$, $p=0.12$).

The effect of physical and mental workload levels on the mental demand (MD) dimension and physical demand dimension (PD) in NASA-TLX was presented in the analysis in order to determine the importance of physical workload effects on the subjective mental demand dimension as stated previously in Chapter 3 (see section 3.2.1). In terms of the mental demand dimension in the TLX score, ANOVA analysis showed that the mental workload levels of both visual tasks had a significant impact on the TLX mental demand dimension ($F(1.8,46.2) = 661.28$, $p<0.01$) (see Figure 4.24). The effect on the physical demand dimension was not significant ($F(1.7,44.2) = 4.13$, $p=0.104$). The effect of physical and workload interactions on the mental dimension was not significant ($F(3.51,90.3) = 0.34$, $p=0.345$). The contrast showed that there was a significant difference between mental workload levels in arithmetic and spatial figures tasks ($p<0.05$ in both cases). Furthermore, there were no significant differences between any of the levels of physical workload ($p>0.05$). The effect of task type factor on mental and physical subscales was not significant ($F(1,26) = 2.46$, $p=0.14$).

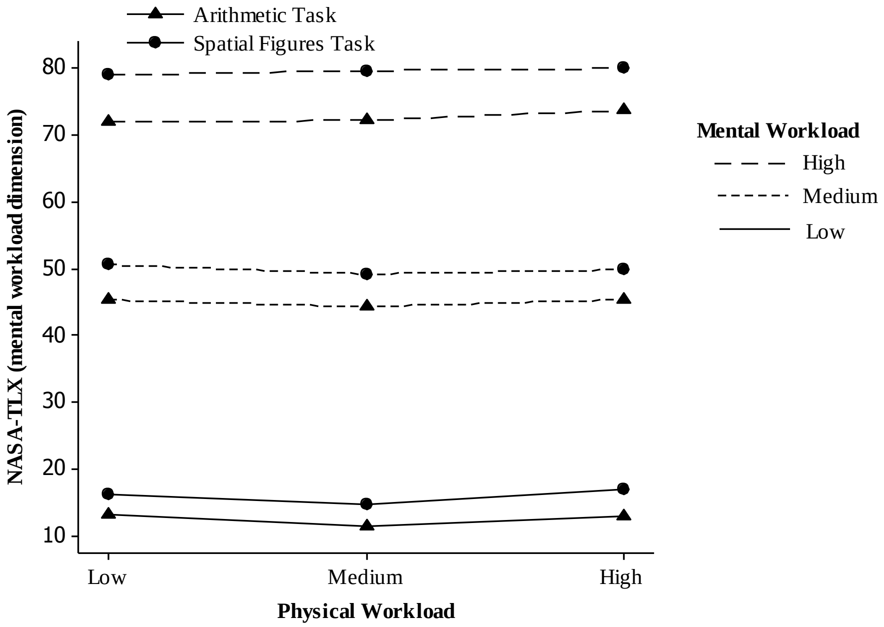


Figure 4.24 Mental demand dimension of TLX for arithmetic and spatial figures tasks against mental workload and physical workload

In terms of the physical demand dimension, the ANOVA showed that physical workloads impacted significantly on NASA-TLX rating ($F(1.81,46.51) = 435.64$, $p<0.01$) Figure 4.25. However, the impact of mental loads on the physical dimension was not significant ($F(1.7,44.3) = 3.72$, $p=0.62$). The effect of physical and mental workload interactions was not significant ($F(3.71,90.51) = 0.77$, $p=0.93$). The contrast showed that there was a significant difference between physical workload levels under all levels of interaction ($p<0.01$).

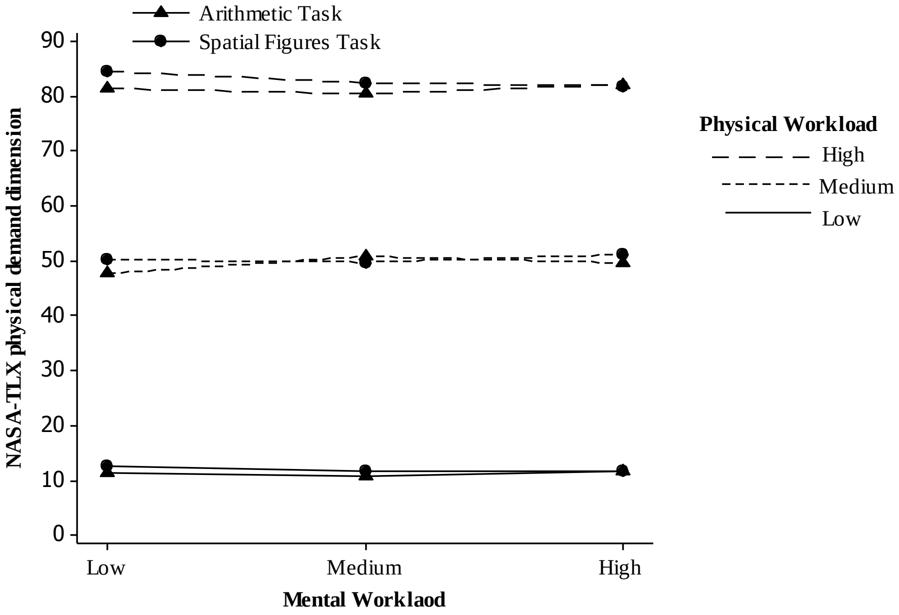


Figure 4.25 Physical demand dimension of NASA of arithmetic and spatial figures tasks against mental workload and physical workload

Gender Differences and Subjective Assessment Tools

Generally, females scored higher in both scales than males, and the impact of the gender variable on CR10 and RPE scores was significant ($p<0.05$ for both). Furthermore, Tukey’s analysis showed that males scored significantly lower than females in both Borg’s ratings at a high level of physical workload (80% Wmax) in both mental task conditions. Figures 4.26 and Figure 4.27 (below) present the gender differences at a high level of physical workload in the arithmetic task and spatial figures task. The same differences between genders occurred at a high level of physical load in both CR10 and RPE scores ($p<0.05$ for both).

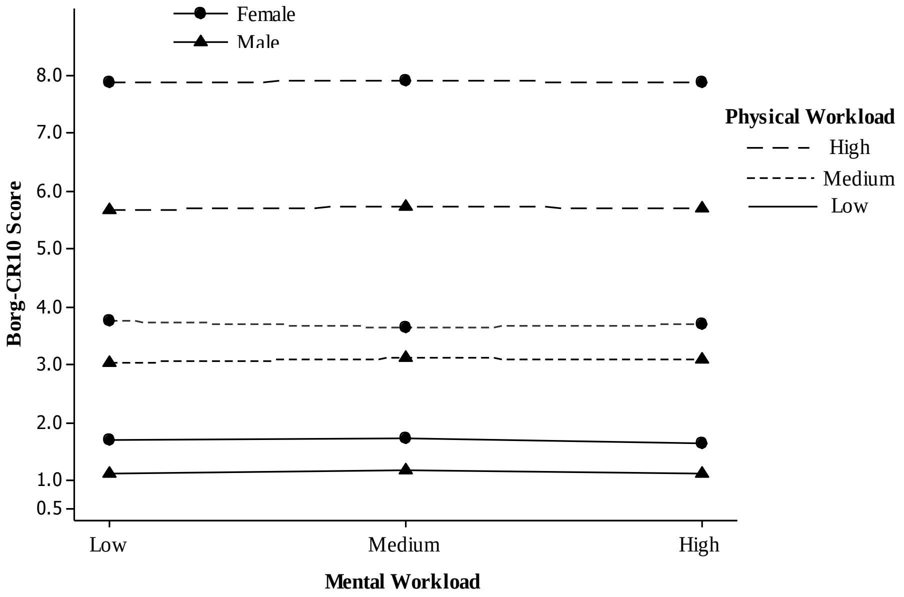


Figure 4.26 Mean of Borg-CR10 scores for males and females in the arithmetic task during physical and mental workload interaction

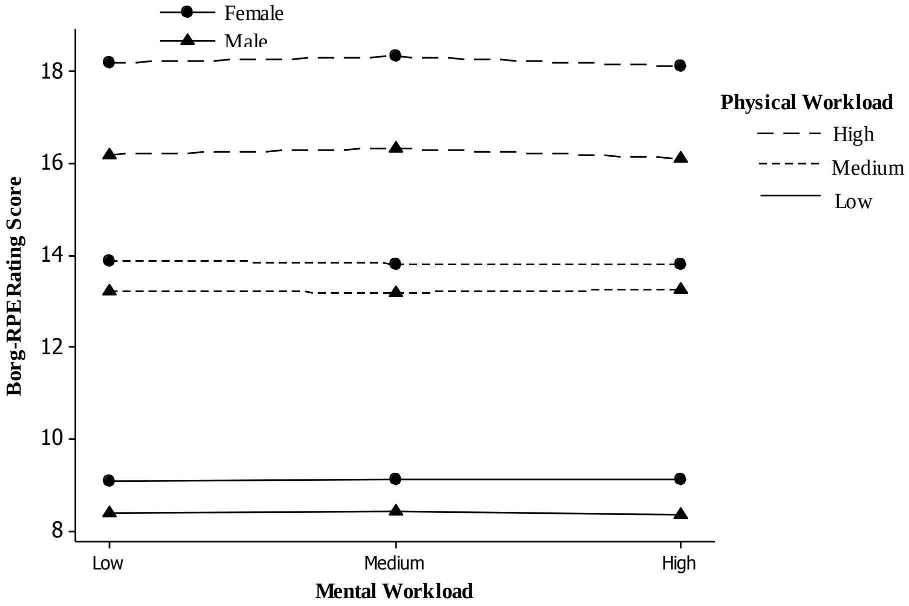


Figure 4.27 Mean of Borg-RPE scores for males and females in the arithmetic task during physical and mental workload interaction

The effect of the gender factor was not significant on the overall TLX score ($F(1,26) = 1.28$, $p=0.123$). Also, the impact of the gender factor on mental and physical dimensions was not significant ($F(1,26) = 1.78$, $p=0.098$) and ($F(1,26) = 1.14$, $p=0.102$, respectively).

4.4.5 Correlation between Objective and Subjective Variables

As mentioned in Chapter 3 (section 3.2.7), Pearson’s correlation (r) was used to classify the relationship between objective and subjective measures as illustrated in Table 4.8. This correlation was used to find out how the performance variables related to the physiological measures (i.e. positive or negative correlation, in particular, the rSO2 variable and how it related to NASA-TLX and Borg’s scales.) Generally, the objective variables were significantly correlated with overall NASA-TLX scores in both tasks. Moreover, HR and MBP were strongly correlated with time of task. The interesting result is that rSO2 (oxygenation changes in the brain) was significantly correlated with HR, MBP, time and NASA-TLX rating (r = -0.37, $p<0.05$; r = -0.36, $p<0.05$; r = -0.36, $p<0.05$; r = -0.43, $p<0.05$, respectively). Borg’s RPE and CR10 scales were correlated with some physiological measures such as HR and MBP.

Table 4.8 Pearson's correlation coefficient matrix (r) for the objective and subjective variables of mental workload (arithmetic and spatial figures tasks) and physical workload interactions

Variables		**HRV**	**MBP**	**rSO2**	**Time**	**Accuracy**	**NASA-TLX scores**	**RPE**	**Borg CR-10 scores**
HR		**-0.61**	**0.53**	**-0.37**	**0.39**	**-0.51**	**0.43**	**0.38**	**0.41**
	p-value	**0.01**	**0.01**	**0.02**	**0.01**	**0.01**	**0.01**	**0.02**	**0.01**
HRV			**0.44**	0.31	**0.38**	0.22	**-0.37**	0.12	0.20
	p-value		**0.01**	0.28	**0.02**	0.21	**0.02**	0.16	0.15
MBP				**-0.36**	**0.41**	**-0.54**	**0.63**	**0.45**	0.32
	p-value			**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	0.05
rSO2					**-0.36**	-0.29	**-0.43**	0.24	0.29
	p-value				**0.02**	0.07	**0.01**	0.09	0.06
Time						-0.28	**0.34**	**0.36**	0.24
	p-value					0.09	**0.03**	**0.03**	0.07
Accuracy							**-0.37**	**-0.32**	**-0.44**
	p-value						**0.02**	**0.04**	**0.01**
NASA-TLX scores								0.30	**0.34**
	p-value							0.06	**0.03**
RPE									**0.61**
	p-value								**0.01**

***bold represents the significance value $p< 0.05$**

4.4.6 Main Findings

Table 4.9 Main Results- First Experiment

Hypotheses	Results
1- The participants' best performance will occur at medium physical workload × medium visual mental (verbal and spatial) workload interactions.	Accuracy was worse ($p<0.05$). However, the total cumulative time of both tasks was better at 50% Wmax vs. medium mental workload but not the best ($p<0.05$). *The hypothesis was rejected*.
2- The participants' worst performance will occur with a high physical workload and high visual mental workload interactions due to the high level of arousal.	In visual mental tasks (arithmetic and spatial figures tasks), the significantly worst accuracy and time of task were observed ($p<0.05$). The hypothesis was not rejected.
3- Participants' performance will be worse with low physical workload × low visual mental workload interactions, due to the low level of arousal.	Performance was better in both visual mental task conditions ($p<0.05$). *The hypothesis was rejected.*
4- Participants' will perform better at medium physical workload × low visual mental (verbal and spatial) workload interactions, due to increase level of arousal caused by medium physical workload.	The performance (accuracy and time of task) was better significantly ($p<0.05$) at a medium physical workload (50% Wmax) and low mental workload. Similar performance was observed at a low physical workload (20% Wmax). *The hypothesis was not rejected.*
5- The participants' best performance will occur with medium physical workload × low visual mental workload. The Participants' will perform better with a medium physical workload × low visual mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.	The performance (accuracy and time of task) was better significantly ($p<0.05$) at a medium physical workload (50% Wmax) and medium mental workload but not the best same as the performance at a medium physical workload and low mental workload. Increasing levels of physical workloads significantly increased the oxygen delivered to the brain by reducing rSO2 (percentage of oxygenation changes) ($p<0.05$). *The hypothesis was rejected for performance at medium workload interactions but was not rejected for other condition.*
6- The participants' worst performance will occur with a high physical workload and high visual mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high visual workload since the increasing level of visual mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the visual workload.	The performance worsened at high physical load × high visual mental workload interactions. This was because of the reduction in brain oxygen since rSO2 was significantly increased at a high visual workload ($p<0.05$). Moreover, there was no significant decrease in rSO2 at medium and high physical levels under medium and high mental workload in either task type ($p<0.05$).*The hypothesis was not rejected.*
7- No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level caused by the physical activity and increase amount of oxygen that delivered to the brain.	There were no gender differences in accuracy and time of task in either visual task ($p<0.05$). *The hypothesis was not rejected for performance.*
8- At high levels of physical and mental workload combinations, men are expected to perform better than women in the visual-spatial task, whereas women will perform better in the visual-verbal task due to the physical workload capacity differences between the genders and high level of arousal.	No gender differences in accuracy and time of task existed in either visual task ($p<0.05$). Females demonstrated higher HR and MBP at high levels of physical workload interacting with low, medium, and high levels of mental workload in the spatial figures task. No gender differences existed in rSO2. *The hypothesis was rejected.*

4.5 DISCUSSION

The purpose of this chapter was to address the following hypotheses as presented in section 4.1:

1. *The participants' best performance will occur at medium physical workload × medium visual mental (verbal and spatial) workload interactions.*
2. *The participants' worst performance will occur with a high physical workload and high visual mental workload interactions due to the high level of arousal.*
3. *Participants' performance will be worse with low physical workload × low visual mental workload interactions, due to the low level of arousal.*
4. *Participants' will perform better at medium physical workload × low visual mental (verbal and spatial) workload interactions, due to increase level of arousal caused by medium physical workload.*
5. *The participants' best performance will occur with medium physical workload × low visual mental workload. The Participants' will perform better with a medium physical workload × low visual mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.*
6. *The participants' worst performance will occur with a high physical workload and high visual mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high visual workload since the increasing level of visual mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the visual workload.*

As mentioned in Chapter 2, most research studies have investigated the impacts of physical and mental workload as separate tasks, but not as a concurrent scenario (Perry et al., 2008). In addition, investigations into the effect of physical and mental workload interaction as a multitask demand under different levels of interaction are very rare (Tomporowski and Ellis, 1986; Tomporowski, 2003). Numerous studies have investigated the impact of different levels of exercises on one level of mental task (Audiffren et al., 2008). This research investigated the impact of physical and mental workload combinations on visual attentional resources, verbal resources (arithmetic task) and spatial resources (spatial figures task). It specifically aimed to understand how the physical workload mechanisms interact with both resource types (visual-verbal and visual-spatial) and how they support the cognitive functions through physiological arousal and supply of more oxygen to the brain. In addition, it aimed to understand the gender differences in various situations of physical and visual mental demand interactions.

4.5.1 Performance Assessments

The findings of this chapter in terms of performance impact showed that accuracy and time of task (total cumulative time of task) were impacted by physical and mental workloads. Unexpectedly, the best accuracy did not occur at medium levels of physical and mental workload interactions in either visual mental task condition. That may be because the medium level of arithmetic and spatial figure tasks used in this chapter were complex for participants. Moreover, the worst accuracy and task times were observed at a high intensity of physical and mental workload in the arithmetic and spatial figures tasks, as it increased stress on visual attentional resources. As a result, the second hypothesis in this chapter was supported: for both mental tasks, the worst performance occurred with overload workload interactions. However, the exciting results in this chapter were that the low physical workload (20% Wmax) led to better accuracy at low mental workload in both mental tasks, same as the accuracy at a medium physical load × low mental workload. This means that the low or medium physical workload is beneficial for visual mental tasks in particular at a low mental workload, so the low and medium physical workloads can avoid any worse performance occurring by a low arousal level due to a low mental workload, as stated by Young and Stanton (2002[a]). In addition, the superior accuracy in both arithmetic and spatial figure tasks appeared at a moderate level of physical × low mental demand, and there were no significant differences between accuracy at low mental workload interactions with low and medium physical loads. Another important result is that the low physical load condition (20% Wmax) led to better accuracy in both visual tasks at the medium mental level, since there were no significant differences in accuracy between low and medium mental workloads at low physical demand in both tasks. In addition, the participants were outperformed at a medium level of physical workload (50% Wmax) in both visual resources at a low visual mental workload in the arithmetic task and spatial figures task, similar to the low physical load condition (20% Wmax). However, in the pilot study (section 4.2.1), there were significant differences between low and medium loads in both visual tasks. In addition, there was a significant difference between the arithmetic and spatial figures tasks at baseline. In contrast, the differences between both mental tasks in accuracy disappeared when interacting with physical workload. This indicated a significant interaction impact of physical and mental workload on accuracy. That may be because of the increasing level of physiological arousal caused by physical activity, which led to better accuracy. This is consistent with Reilly and Smith's (1986) results. The researchers found that the performance of a visual task with physical activity is better than performing the same task while at rest level. In addition, Mozrall and Drury (1996) stated that physical loads lead to an increase in arousal level, so cognitive information is facilitated. In addition, physical activity transports more blood and oxygen to the brain, which leads to a reduction in the percentage of oxygenation changes in the brain due to increased mental activity (Perrey et al., 2010). Therefore, the participants performed better at low and medium physical workloads versus low and medium mental workloads in both visual arithmetic and spatial figures tasks rather than at the baseline condition. This result does reject the third hypothesis of this chapter, which proposed that performance would worsen at low mental workload × low physical workload interactions due to a low arousal level. In addition, the Pearson's correlation indicated a moderate negative correlation between accuracy and HR ($r = 0.51$, $p < 0.05$) and MBP ($r = 0.54$, $p < 0.05$), which means that the worse accuracy is associated with increased HR and MBP.

In the task time results, time became better at the medium level of physical workload (50% Wmax) × medium mental workload interactions in both visual tasks but not the best, similar to the time of task at the medium level of physical workload (50% Wmax) × low mental workload. There were no significant differences between time in either visual task at low and medium mental workloads at medium physical activity. In contrast, there was a significant difference in time between low and medium mental workloads under baseline conditions in both arithmetic and spatial figures tasks. Furthermore, in baseline conditions (see first pilot study, section 4.2.1), the spatial figures task took more time than the arithmetic task at medium level. In contrast, at medium physical load, the differences between the tasks were not significant at low and medium mental workload levels. This means that the medium physical workload positively affected the time of mental visual tasks. This is because the increased level of physical workload led to an increase in physiological arousal level, improving visual information processing and leading to better performance. In addition, the medium level of physical demand led to low brain activity through reduction in the oxygenation changes by increasing the amount of oxygen delivered to the brain. These results were consistent with previous studies that mentioned how the superior time in a visual psychomotor task occurs at a medium level of physical workload (38% VO2 max) (Reilly and Smith, 1986). This finding is similar to the results of some studies (e.g., Arcelin et al., 1998; Davranche and Audiffren, 2004) that contended that moderate levels of exercise facilitate the speed of information processing and reaction times for visual mental tasks. As a result, the first hypothesis in this chapter was not rejected for both mental tasks in which the time at medium mental workload was superior to that of the medium physical workload. Furthermore, Pearson's correlation test presented considerable negative correlation between rSO2 and time of task (r = -0.36, $p < 0.05$). Furthermore, there was a high correlation between time of task and the physiological variables HR and MBP.

4.5.2 Physiological Parameters

Generally, all physiological measures responded to the changes in physical and mental workloads and combinations. Significant increases in HR and MBP were associated with physical and mental workload increases in both visual mental tasks. This indicated that both increasing levels of physical loads and mental workloads in both mental tasks impacted significantly physiological arousal. HR increased significantly when physical and mental workload increased. This was consistent with previous experimental studies (Arcelin et al., 1998; Fredericks et al., 2005;

Hogervorst et al., 1996), which found that the HR of participants was affected by the complexity levels of the mental workload in the form of arithmetic and monitoring tasks. Also, HRV was sensitive to both mental and physical workloads since it decreased significantly as visual arithmetic and spatial figure tasks increased. Conversely, HRV increased when physical workload increased. This was consistent with previous experimental studies (Sammer, 1998; Tomporowski, 2003), which found that the HRV of participants was affected by the complexity levels of the mental workload tasks.

On the other hand, the effect of physical workload is significant and positive, since an increase in HRV means an increase in physical activity (see Rennie et al., 2003; Sammer, 1998). Also, the mean of the blood pressure parameter was significantly impacted by the physical and mental workload interactions in both the arithmetic and spatial figures tasks, given that the MBP increased significantly when the workload interaction of physical versus arithmetic (mental) and physical versus spatial figures (mental) increased. This was similar to previous results, notably Fredericks et al. (2005), who found that the blood pressure increased significantly during intensive levels of physical cycling and calculating problems.

The results of that study proved that an incremental increase in physical workload from a low level to a moderate level leads to increased physiological arousal, and better performance in both visual verbal tasks (arithmetic) and spatial tasks (spatial figures) occurred at moderate levels of physical workload (50%) and low mental visual workload. Furthermore, the current study found that a moderate physical level leads to better time of task at medium physical (50% Wmax) vs. medium mental workload in both mental tasks, similar to the time at low physical load (20% Wmax) vs. medium mental load since the time differences were not significant. The participants performed better under these physical and mental workload interaction conditions due to an increased level of arousal due to physical activity. These results are similar to those of Audiffren et al. (2009), who found that a medium level of pedalling leads to better accuracy and visual reaction time due to the increase in arousal level associated with increased physical loads.

Generally, no significant differences were found between either visual task concurrent with physical activity in HR and MBP under all levels of workload interactions, whereas under baseline conditions the spatial figures task was seen to be more difficult than the arithmetic task, since it showed a higher HR than the arithmetic task. That may because the visual-spatial task needs more time to complete and also requires more information processing than the arithmetic task, such as orientation processing. Also, the spatial figures task resulted in a lower HRV, while cycling, than the arithmetic task. According to Veltman and Gaillard (1996), the HRV measure is very sensitive to complex mental tasks so HRV decreases significantly when mental task level increases. This was consistent with Halpern's (2000) results, which indicated that spatial information processing is usually more complicated than verbal processing since the individual needs to use data in long-term memory to recall the shape and orientation process; however, the difficulty depends on the type of task.

4.5.3 Brain Activity

As mentioned in Chapter 3 (section 3.2.5.3), the NIRS technique was used to measure the Regional Cerebral Oxygen Saturation (rSO2) to reflect the percentage of oxygenation changes in the frontal region of the brain during physical and visual mental workloads, so it shows the effect of workload on attentional resource capacity.

The impact of physical and mental workload interactions on rSO2 was significant. Since, increaseed levels of visual mental workloads (arithmetic and spatial figures tasks) increase the percentage of oxygenation changes in the brain (brain activation) to meet the increase in mental demands, since increasing brain activation indicates an imbalance between the amount of oxygen that exists in the brain and the amount that is needed to meet a high mental workload. This is consistent with Kikukawa et al. (2008) who found that increasing levels of visual mental demand in aircraft pilot tasks leads to poor performance. This is supported by Menon et al. (2000) and Rueckert et al. (1996), who stated that mental stress due to high mathematical loads leads to an increase in the cerebral oxygen that reaches the brain (rSO2), since the brain needs a greater activation process to respond. On the other hand, the increasing level of physical activity from low level to medium led to a reduction in the activation of the brain, since more blood is pumped to the brain and so the delivered oxygen to the brain increases, which reduces the oxygenation changes in the brain. As a result, it may be that the participants' were performed better at low and moderate physical workloads. Furthermore, there was a significant negative correlation between rSO2 against HR and MBP (r = -0.37, $p < 0.05$ and r = -0.36, $p < 0.05$), respectively. According to these results, the effect of physical workload on rSO2 at a high mental visual workload was not significant, since there were no significant differences between rSO2 at the medium and high physical demands at the high mental workload. This is because before the fatigue stage and at a high level of physical intensity, the other muscles of the body require more oxygen to meet the physical workload, as does the brain, so the available oxygen is being shared by the brain and the other muscles (Perrey et al., 2010). The visual spatial figures task concurrent with cycling showed higher rSO2 percentages (i.e., higher brain oxygenation changes) than the visual arithmetic task (verbal) at high mental workload level interactions. This means that the differences between the amount of oxygen that available in the brain and the amount that needed to complete the spatial figures task were greater than arithmetic task. Finally, the impact of task type (arithmetic and spatial figures tasks) factor on rSO2 was not significant.

4.5.4 Subjective Assessment Tools

Physical Workload Assessment (Borg's scores)

The Borg-CR10 and RPE scores were used to measure the physical demands in both experiments. The Borg-CR10 and RPE ratings were sensitive to increases in physical workload because an increase in physical workload for both tasks led to an increase in Borg-CR10 and RPE. The score was not, however, sensitive to mental workloads in either visual task condition. These results were supported by several studies that proved that the Borg-CR10 and RPE scores were affected by increased difficulty in physical loads, and these tools are commonly used to measure physical demands (Borg, 1982; Borg, 1998; DiDomenico and Nussbaum, 2008). Furthermore, the results showed that there was a significant difference between CR10 scores at a low physical workload versus at a medium physical workload and at a medium physical load versus at a high physical workload. The same applied to RPE scores. One important piece of information to be derived from these results is that the visual cognitive workloads did not impact participants' perceptions of physical workload. Thus, participants did not perceive any changes in physical load level due to mental workload, and there was no influence on physical subjective assessment tools by mental workload activities. Furthermore, the Pearson correlation indicated a moderate positive correlation ($r = 0.61$, $p < 0.05$) between CR10 and RPE scores, which means that an increased CR10 score is associated with an increased RPE score. In addition, 37% of the variation in the CR10 scores is accounted for by the variation in the RPE score. Both scores were significantly linear, and they increased along with an increase in physical workload. Both scales were used, however, because various individuals make physical workload judgments differently. Although some individuals evaluated physical loads based on the range of effort that occurred due to physical activity (reflected by the RPE scale), others rated physical loads depending on the range of pain that occurred throughout the physical activity (reflected by the CR10 scale; Borg, 1998; as stated in Chapter 3, section 3.3.2.4). Hence, any removal for either score would not impact the research findings negatively.

NASA-TLX Assessment Tool

In terms of overall NASA-TLX score, the TLX rating scores were significant with an increase in physical and mental arithmetic task workloads, because the physical dimension was included in this scale. The impact of physical and mental workload interaction was not significant. However, an increase in physical and spatial figures of mental workload interaction led to an increase in the NASA-TLX score. That may be because the physical loads affected the subscales in the TLX (i.e., performance, frustration, effort and time dimensions). Researchers normally use TLX scores to evaluate mental workload and neglect the physical demand subscale, so according to the current results, physical activity should be considered together with mental workload in any task that includes physical effort, because physical workload had a significant impact on overall TLX scores. The results were similar to other studies that found that the NASA-TLX score is sensitive to the interaction of physical and mental demands (Fredericks et al., 2005; Jung and Jung, 2001). However, the differences in TLX scores between visual and mental tasks were not significant at all levels of workload interactions. However, the Pearson's correlation indicated that a weak positive correlation overall TLX score and accuracy and time of task ($r = -0.37$, $p < 0.05$ and $r = 0.34$, $p < 0.05$), respectively. However, the lowest scores occurred at the simple interaction condition of physical workload versus mental arithmetic tasks and spatial figures mental tasks. The results found a significant (albeit weak) correlation between the TLX overall workload scores and the CR10 ratings ($r = 0.34$, $p < 0.05$), although the correlation between TLX and RPE only approached significance ($r = 0.30$, $p = 0.062$). Thus whilst there is some redundancy between the TLX and Borg's ratings for physical tasks, there are clearly still some significant elements of each of these complex subjective constructs that are not being accounted for in the other.

In terms of the TLX mental demand dimension, the results showed that the NASA-TLX rating was significantly affected by an increase in mental arithmetic workloads and spatial figures workloads. This is supported by various research studies that point out that the NASA-TLX score is influenced by an increase in the mental workload (Hart and Staveland, 1988; Hwang et al., 2008). The effect of physical workload levels on the mental demand dimension was not significant. Additionally, the effect of workload interactions on the mental demand subscale was not significant. That means the changes of physical workload did not impact on subjective mental dimension assessments. In addition, the physical workload changes did not affect the participants' judgment on mental visual workload tasks. In contrast, as mentioned previously, the physical workloads did affect the overall TLX score, possibly because it was influenced by other dimensions such as performance, effort and time TLX dimensions. This is similar to a previous study (DiDomenico and Nussbaum, 2008) that found no significant impact of physical loads on the mental demand dimension.

In terms of the TLX physical demand dimension, the findings showed that the TLX was significantly affected by the workload of difficulty of the physical load changes. The score significantly increased as physical workload increased. The physical dimension was sensitive to physical load changes, similar to Borg's scores (CR10 and RPE), since the results showed significant differences between low versus medium physical load and medium versus high physical load. These results were consistent with previous results that have shown that the TLX scores are sensitive to physical load change difficulty levels and there is positive correlation between Borg's scores and the NASA-TLX physical demand dimension (DiDomenico and Nussbaum, 2008; Fredericks et al., 2005). However, the effect of mental workload changes for both visual tasks did not significantly impact on the physical subscale. In addition, the influence of workload interactions was not significant on the subjective physical scale in TLX rating. Thus, the effect of visual workload level alteration did not impact on participants' perception towards physical loads changes.

4.5.5 Gender Differences

7. *No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level caused by the physical activity and increase amount of oxygen that delivered to the brain.*
8. *At high levels of physical and mental workload combinations, men are expected to perform better than women in the visual-spatial task, whereas women will perform better in the visual-verbal task due to the physical workload capacity differences between the genders and high level of arousal.*

Gender Differences and Performance

The gender factor did not impact on participants' performance (accuracy and time of task) with any level of workload interaction. This may be because the physical demands in this experiment facilitated information processing in visual tasks, so the differences disappeared. This supports the hypothesis of this experimental study. This is similar to the findings of Yagi et al. (1999), who found no significant difference between males and females in visual reaction accuracy and time when performed concurrently with low and moderate cycling. Nevertheless, an unexpected result was that there was no significant difference between males and females at high of workload interaction in either mental task. This may be because the visual tasks that were used in this chapter were not difficult and the physical workloads were calculated depending on each participant's physical workload capacity, so the gender difference and effect at a high workload of physical load decreased.

Gender Differences and Physiological Parameters

In general, females presented higher physiological means than males in HR and MBP during the spatial figures task at a high physical workload × low mental load, high physical workload × medium mental workload and high physical workload × high mental workload. This may be because the physical capacity and strength of the female is generally lower than male, which may have had an impact on the physiological variables. This is consistent with Yagi et al. (1999) who found that females had a higher HR than males while performing visual reaction time tasks at a high workload of physical activity. In contrast, there were no significant differences in HR and MBP between genders in the arithmetic task. Furthermore, there was no significant gender difference in HRV in either visual task.

No gender differences in brain oxygenation occurred under any level of mental and physical workload interaction in either auditory task. That may be because the relationship between physical and rSO2 was negative, since the increasing workload of physical cycling produced less brain oxygenation changes and so mean rSO2 was reduced. That may be because the physical workload translated more blood, and thus oxygen, to the brain while performing the auditory tasks (Antunes et al., 2006; Perry et al., 2009), which may lead to a reduction in the differences in oxygenation changes in the brain between genders.

Gender Differences and Subjective Assessment Tools

In terms of Borg's CR10 and RPE scales, females scored higher than males in both mental tasks and at a high level of physical workload. However, the strongest gender difference appeared at high levels of physical workload. That is because the physical workload capacity of males is greater than that of females, which relates to muscle structure and strength (Borg, 1998). This result is consistent with the physiological measures of HR and MBP, which increased significantly with physical demands.

In terms of the NASA-TLX score, there were no significant gender differences between males and females in the MD rating score in either visual task, and also there were no significant differences in overall TLX score. There were no significant differences between males and females in overall NASA-TLX score in either visual task condition concurrent with physical exercise. That may be because women took more time than men to complete the visual arithmetic and spatial figures tasks while cycling. However, Hancock et al. (1988) mentioned that the differences between males and females in TLX score depend on the difficulties of cognitive tasks, with the differences appearing when dealing with more complex mental tasks where females score higher than males.

4.6 CONCLUSION

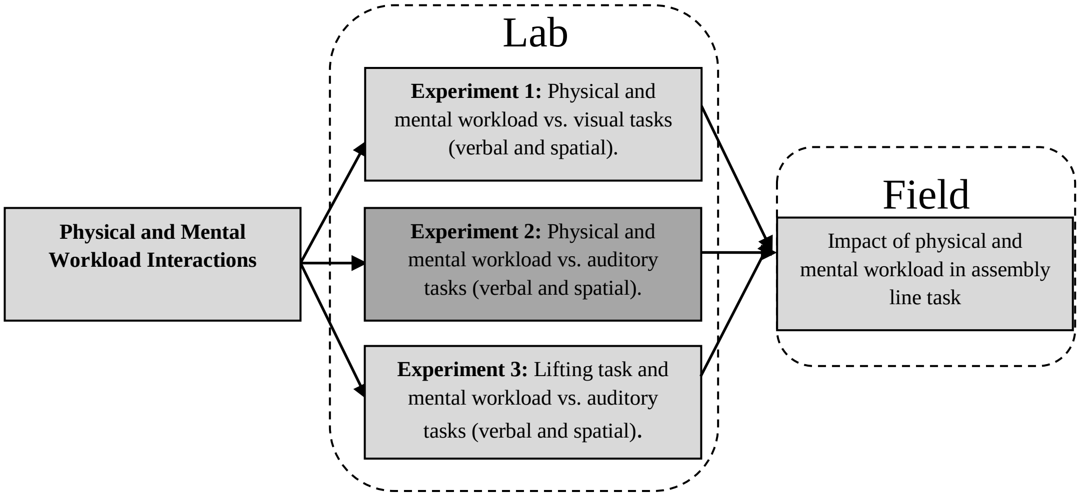
In conclusion, this chapter examined the mechanism of physical and mental workload interactions on visual resources; an arithmetic task (verbal resources) and spatial figures task (spatial resources). Generally, the low and medium of physical workloads leaded to better performance of both visual tasks and no significant differences occurred between the tasks in accuracy and time taken to complete, at all levels of mental and physical workload interaction. This explains how the different levels of physical workloads can affect visual information processing through increasing the physiological arousal level. Furthermore, it investigated how low and medium of physical workload lead to better performance in visual resource performance, rather than baseline, through supplying more oxygen to the brain during mental task performance.

The results of this chapter showed that the participants performed better at low physical workload (20% Wmax) and medium mental workload interactions in both visual tasks since there were no significant differences between accuracy at low and medium mental workloads at low physical activity, whereas there was a significant difference between low and medium levels in both visual tasks under baseline conditions. Moreover, medium physical workload led to better accuracy at a low mental workload level in both visual tasks but not the best. Also, the results showed that a medium level of physical workload (50% Wmax) led to better task times at medium mental workloads in both tasks since there was no significant difference between task times at low and medium mental workloads versus a medium physical load. In contrast, the differences between task times under baseline conditions were significant in both visual tasks. This, therefore, indicates that low and medium physical workloads lead to better performance (i.e., accuracy and time of task) at low visual mental workloads for both visual resources in Wicken's model (1984), which are visual-verbal and visual-spatial resources, by increasing the level of physiological arousal and thus boosting oxygen delivery to the brain. In addition, the results showed that there were no significant differences between task times at a low mental workload with low and medium physical workloads. Furthermore, the participants observed better task times at a medium physical load and medium visual mental demand in the arithmetic and spatial figure mental tasks. Thus, the low physical workload positively impacted accuracy at low and medium mental workloads in the arithmetic and spatial figure tasks. In addition, medium physical loads positively impacted the completion time of visual tasks at low and medium mental loads since the time taken to complete the tasks was faster than at the baseline condition, which may be due to the physical load increasing the amount of oxygen delivered to the brain. In contrast, an overload of physical and mental workload interactions led to the worst performance. Therefore, the current results proved the significant contribution of physical workloads on visual tasks. Chapter 5 investigates the effect of physical and mental workload combinations on the second perceptual input of the attentional resources model, auditory resources. The current chapter concludes that there were no significant differences between visual-spatial tasks and visual-verbal tasks while performed simultaneously with physical activity, although the visual-spatial task was more difficult than the verbal task under baseline conditions. However, there were no significant differences between genders in performance on the arithmetic or spatial figure tasks. However, the physiological measures showed a significant difference in the spatial figure task at high levels of workload interactions, and these measures showed that workload interactions were more demanding for females rather males.

More importantly, this chapter found that the NIRS method is a valuable technique that reflects the impact of physical and mental workload on attentional resources through measuring the percentage of oxygenation changes in the brain. Also, the results showed that the overall NASA-TLX was a valuable subjective measure for evaluating the overall workload in a multitasking scenario. Borg's scores were confirmed to be sensitive to physical workload changes.

CHAPTER 5 -Experiment 2:

INFLUENCE OF PHYSICAL AND MENTAL WORKLOAD INTERACTIONS ON AUDITORY ATTENTIONAL RESOURCES PERFORMANCE



5.1 INTRODUCTION AND EXPERIMENTAL HYPOTHESES

As stated in Chapter 3, the current chapter investigates the influence of physical and mental workload combinations on auditory tasks (arithmetic-verbal tasks and tone localisation-spatial tasks). In Chapter 4 the impact of physical and mental workload interactions on visual tasks was investigated. Generally, the results of Chapter 4 showed the positive and significant effects of low physical workload (20% Wmax) and medium physical workload (50% Wmax) on visual mental task performance (arithmetic task and spatial figures task).

However, according to the literature review in Chapter 2, studies that investigate the impact of physical and cognitive tasks on auditory resources have been found different results since, some researchers found that the moderate physical impact positively on auditory task performance whereas, other researchers conclude that the performance significantly worse in particular at high physical workload (Yagi et al., 1999). Furthermore, the majority of previous papers have investigated the effect of various physical loads on simple auditory arithmetic tasks or tone reaction time tasks at one level of mental workload (Joyce et al., 2009). The interaction impact of different physical and mental auditory workload combinations has received less attention. So this experiment aimed to examine the impact of physical and mental workloads on verbal and spatial auditory tasks (arithmetic and tone localisation respectively). Audiffren et al. (2009) found that an intermediate level of cycling exercise facilitated an auditory verbal random number generator task since it improved accuracy and time. They also mentioned that high-intensity levels of physical workload (90% VO_2 max) led to performance declines in an auditory ascending number task due to an increased level of physiological arousal. In addition, moderate exercise (40% Wmax) improved auditory spatial tasks (tone identification RT tasks), accuracy and reaction time (Joyce et al., 2009). However, according to Audiffren et al. (2008), the correlation between physical workload and cognitive auditory tasks follows an inverted-U line, as that between mental demands and performance. Therefore, the hypothesis for this experiment is as follows:

- *The participants' best performance will occur at medium physical workload × medium auditory mental (verbal and spatial) workload interactions.*
- *The participants' worst performance will occur with high physical workload and high auditory mental workload interactions due to the high level of arousal.*

Chapter 4 indicated that the better performance of participants in visual verbal and spatial tasks occurred at low levels of workload interactions. The same occurred regarding performance at a medium physical level versus a low mental level, which may be due to the increased level of arousal caused by physical activity, which can allow participants to avoid any reduction in visual resource capacity caused by a low mental workload, which means a low level of arousal. In addition, as mentioned in the literature review, some authors have suggested that mental performance decreases under mental tasks that are simple (Wilson and Russell, 2003), due to the low level of arousal (in terms of physical activity). Some researchers have pointed out that the worse performance in auditory tone reaction times occurs due to low levels of arousal (Audiffren et al., 2008). Furthermore, previous researchers have studied the effect of mental demands on auditory task performance (Lee, 2001). Thus, the hypothesis derived from this review is as follows:

- *Participants will perform better at medium physical workload × low auditory mental (verbal and spatial) workload interactions due to an increased level of arousal caused by the physical workload. .*
- *Participants' performance will be worse with low physical workload × low auditory mental workload interactions due to a low level of arousal.*

As mentioned in Chapter 2, Perrey et al. (2010) stated that brain measures could indicate how physical demands can support attentional resource capacity, since cognitive functioning during auditory mental tasks may be better because of the supply of more oxygen to the brain; this oxygen is utilised by the frontal lobe, so the oxygenation then decreases and information processing improves. This means that increasing levels of oxygenation changes in the brain are associated with increasing loads of auditory cognitive tasks (Hershfield et al., 2009). Kashihara et al. (2009) stated that a high level of auditory arithmetic task (verbal) leads to high brain activation. No study has investigated the effects of physical and mental workload combinations on brain activity (Perrey et al., 2010). In addition, moderate physical activity could supply more blood and oxygen to the brain and that could support auditory information processing through balancing the amount of oxygen in the brain and the amount needed to meet the mental workload (Antunes et al., 2006). Therefore, in terms of regional tissue oxygenation (rSO2) the hypothesis derived from this review is as follows:

- *The participants' best performance will occur with medium physical workload × low auditory mental workload. The participants will perform better with medium physical workload × medium auditory mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of the physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.*
- *The participants' worst performance will occur with high physical workload and high auditory mental workload interactions due to the reduction in the amount of*

brain oxygen (low blood flow) delivered to the brain caused by the high auditory workload since the increasing level of auditory mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the auditory workload.

According to the review in Chapter 2 (section 2.3.2), the differences between males and females in auditory cognitive tasks depend on the type of mental tasks, as some researchers have found significant differences, whereas others did not find any significant differences in auditory tasks (Halpern, 2000). According to Spierere et al. (2010), males perform better than females in spatial auditory tasks, and females perform better in auditory verbal tasks. For example, one study concluded that men outperform women in sound localisation tasks, such as audio-spatial tasks (Zundorf et al., 2011). However, the difference between the genders in verbal and spatial auditory tasks decreases at low and medium levels of physical exercise by increasing the level of arousal level, which, in turn, increases the level of auditory resource capacity and leads to better performance in both genders, and differences disappear, as confirmed in the study by Yagi et al. (1999); however, they used a simple auditory mental task (a tone reaction-time task). Indeed, no study has yet examined the gender differences in auditory tasks under different levels of physical and mental workload combinations (Yagi et al., 1999). Nevertheless, Yagi et al. (1999) stated that significant differences occurred between genders at a high level of physical load since; there is a variation between genders in physical strength and capacity. In general, there is a significant difference between the genders in physical load strength and capacity (Lindbeck and Kjellberg, 2001). Therefore, in the current experiment in term of gender differences, the hypothesis for this experiment is as follows:

- *No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level caused by the physical activity and increased oxygen delivered to the brain.*
- *At high levels of physical and mental workload combinations, men are expected to perform better than women in the auditory-spatial task, whereas women will perform better in the auditory-verbal task due to the physical workload capacity differences between the genders and the high level of arousal.*

The hypotheses that were presented previously were derived from the main hypothesis of the thesis (see Chapter 2, section 2.8) and were not dependent on the results of Chapter 4, since each main experiment was included in the main hypotheses that were derived from the literature review.

5.2 STEP ONE-PILOT STUDY

The pilot study was implemented in order to find out whether the two mental auditory tasks selected to produce the mental workload (arithmetic and tone localisation task), satisfied the difficulty levels or not, since each task has three workloads (low, medium and high). The section below explains the details of both pilot studies. The differences in difficulty workloads of the arithmetic task were satisfied in the previous chapter for visual tests, but in this section they were tested for difficulty workloads in an auditory scenario.

5.2.1 Experimental Design

The current pilot study was conducted to validate and verify the impact of three difficulty levels of mental workloads for two auditory tasks: an arithmetic task (verbal task) and a tone localisation (spatial) task; the experiment was a full factorial repeated measures design.

The arithmetic mental task details and levels were similar to the arithmetic task used in Chapter 4 (see section 4.2.1) but in this experiment they were presented aurally. The arithmetic task was used to reflect the impact of auditory mental workload on auditory-verbal resources. The three difficulty workloads were subject to validation in this pilot study. These workloads are: low (addition/subtraction numbers between 1 and 10), medium (addition/subtraction problems with two numbers between 3 and 35) and high (addition/subtraction problems with two numbers between 20 and 150 for the subtraction operation and between 20 and 150 for the addition).

The auditory tone localisation task was used to reflect the impact of auditory mental workload on spatial auditory resources. This depends on the number of simultaneously presented auditory sources or workload, which was six speakers placed at 270^o, 30^o, 60^o, 90^o, 120^o and 150^o inside a room 3 m in diameter, around the participant; the layout is as shown in Figure 5.1 This type of auditory load was used previously by Lee (2001). Two tones were generated by an NCH tone software generator (ToneGen v.3 NCH Software Pty Ltd, Australia). In each trial the participants needed to select the speaker that generated a pure tone. This type of test was performed to examine the effect of workload interaction on auditory searching/load; this task included the following three levels:

1. For the low level, participants were asked to determine the source of pure tone between two speakers placed at 270^o and 30^o (auditory localisation task).
2. For the intermediate level, participants were asked to find the source of the pure tone with four speakers in different positions (270 ^{o}, 30^o, 60^o and 90^o).
3. For the difficult level, participants were asked to detect the auditory pure tone with six speakers (270^o, 30^o, 60^o, 90^o, 120^o and 150^o).

Each speaker was assigned a number, from 1 to 6, as shown in Figure 5.1.

These three levels of mental workload were validated by Lee (2001). However, this pilot study was implemented to verify these three difficulty levels for the present study. The mental task workloads were used in order to satisfy the level of mental auditory workloads from the low level to the difficult one.

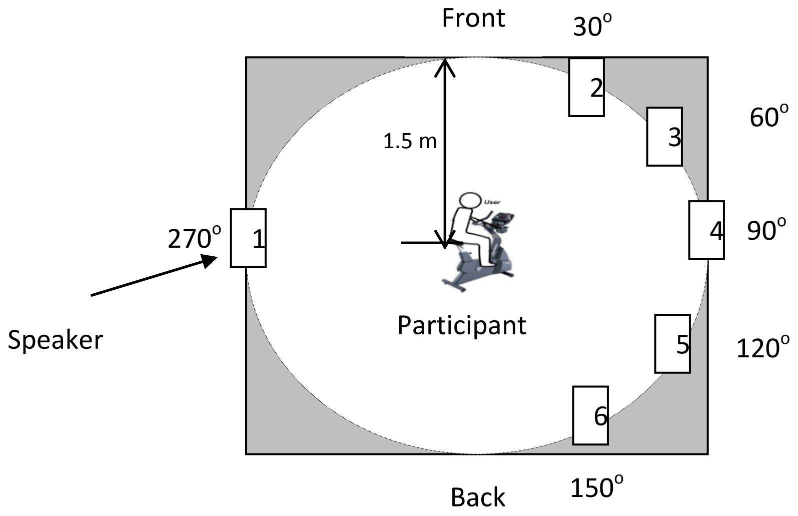


Figure 5.1 Schematic diagrams of the experiment apparatus with the auditory workload level speakers

The goal of this trial was to examine the user's ability to localise the target, which was set at 700 ms duration for each trial and a frequency of 2 kHz. This type of auditory task has been used to reflect the mental auditory load on spatial resources in previous studies (Kilgore, 2009; Mondor and Zatorre, 1995). According to Mondor and Zatorre (1995), the tone localisation task places an attention demand on the auditory spatial resource. For instance, the tone localisation task requires users to determine the particular position (speaker) that produces the pure tone under the different location distributions of the speakers. There are three main dependent variables: performance (accuracy and cumulative time of total task [time of task]); physiological indices, which includes heart rate (HR) and heart rate variability (HRV), to reflect the physiological arousal effect of mental workload; the NASA-TLX subjective assessment tool was used to measure mental workload.

5.2.2 Participants

Twelve participants (aged 25 –35) were invited through an announcement issued on the website of Brunel University. This sample size included six males and six females who were chosen in order to find one standard deviation for the independent variables as well as normality. The statistics for the participants are illustrated in Table 5.1. All participants had normal hearing. The same sample was utilised for both studies. Participants were invited to participate through the University website. The study was approved by the Brunel University Ethics Committee (see Appendix D).

Table 5.1 Explanation statistics for sample size

	Male(n=6)		Female (n=6)	
Variable	Mean	SD	Mean	SD
Age (year)	29.2	2.70	28.8	3.11

5.2.3 Procedure

At the beginning, participants were given a brief introduction to the experiment in order to familiarise them with the steps. They were also provided with instructions and advice on how to perform an auditory arithmetic mental task and tone localisation task. The participants from the previous experiment participated in this experiment and counterbalancing and randomisation between the two tasks were taken into account by the number generator software. Then the participants were asked to affix the chest electrodes for the heart rate monitor to their chests so that the researcher could record HR and HRV continuously for each participant as they completed the assigned tasks.The first experiment began with the presentation of the arithmetic tasks through the speakers, using a male voice at 70 dB (A) and with similar questions to those described in section 4.3. (e.g. 34 + 56 = ?) . The participants were presented with the levels of difficulty randomly in order to reduce potential carryover effects and fatigue. Each participant completed 25 questions within each level as accurately and quickly as possible in the allotted six minutes. The number of correct responses and the actual time required to complete the section were recorded directly by the software. Also, immediately after completing each trial, participants were asked to complete the NASA-TLX scale in the two to three minute interim between each level.

In the second experiment (i.e. tone localisation), speaker number 1 was fixed across all levels, so at the low level participants were asked to select from two speakers (1 and 2), one of which produced pure tone while the other produced white noise concurrently. The participants were asked to select the number of the speaker that produced pure tone. For the medium level, they were asked to determine the pure tone while speakers 1, 2, 3 and 4 produced the pure tone or white noise concurrently. For the high level tone localisation task they were asked to identify the speaker producing the pure tone while all six speakers were activated. They answered by choosing the correct speaker position through entering the number of the correct speaker via a keyboard. Measurements were recorded with identical equipment to that in the previous experiment. The speakers were placed in the room in different positions and were assigned a number. The speaker placed at 270^{o} from the participant was assigned number 1; number 2 at $30^{o;}$ 3 at $60^{o;}$ 4 at $90^{o;}$ 5 at 120 and at 150^{o}, 6. Each condition included 25 problems, and participants were given six minutes to complete each level. In addition, they took two to three minutes to rest and complete the NASA-TLX Score (see Appendix G) between each condition.

5.2.4 Results

5.2.4.1 Participant Performance

Participant performance was measured by recording the accuracy and time of task for the auditory arithmetic and tone localisation tasks. Mauchly’s test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was met for accuracy and time of task parameters (p>0.05).

Participants Accuracy and Time of Task

In this section the accuracy of participants and the cumulative time of task (time of task) for auditory tasks (arithmetic and tone localisation tasks) were analysed and both were related to task difficulty levels. The ANOVA technique showed that the levels of difficulty of the auditory arithmetic and tone localisation tasks significantly affected participants' answer accuracy ($F(2,22) = 50.85$, $p<0.01$). Also, a repeated contrast test illustrated that there was a significant difference between the low workload and the medium workload of the arithmetic test ($p<0.05$) and between the medium and high workloads ($p<0.05$). Furthermore, a significant difference was observed between the low workload and the medium workload of the tone localisation task ($p<0.05$), and between the medium and high workloads ($p<0.05$). However, there was no significant impact of task type interaction on their workloads of accuracy ($F(2,22) = 0.348$, $p=0.724$). The effect of task type on accuracy was not significant ($F(1,11) = 2.25$, $p=0.\ 084$).

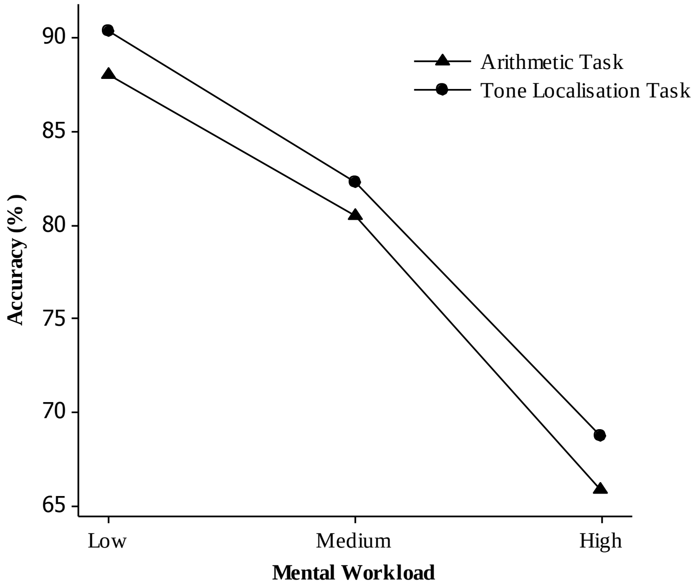


Figure 5.2 Accuracy implies correlation the three levels of mental workload for both arithmetic and tone localisation mental tasks

The ANOVA showed that the levels of difficulty of the auditory arithmetic and tone localisation tasks significantly affected the participants' speed (*F*(2,22) = 176.672, *p*<0.01). According to repeated contrast analysis a significant difference was observed between the low workload and the medium workload of the arithmetic test (*p*<0.01), the difference between the medium and high workloads of arithmetic task was also significant (*p*<0.01). On the other hand, no significant impact of task type interaction on time of task was observed (*F*(2,22) = 0.46, *p*=0.922).

Moreover, repeated contrasts revealed a significant difference between the low workload and the medium workload of the tone localisation task (*p*<0.01), also the difference between the medium and high workloads of the tone task was significant (*p*<0.01). Finally, when the tasks workloads (arithmetic and tone localisation) increased, the time of task increased (Figure 5.3). The effect of task type was significant on time (*F*(1,11) = 13.46, *p*<0.05). Generally, participants took more time on the arithmetic task than on the tone localisation task. Furthermore, the Tukey HSD revealed significant differences between both tasks at medium and high levels (*p*<0.05). There were no significant differences between time in both tasks at a low level (*p*=0.123).

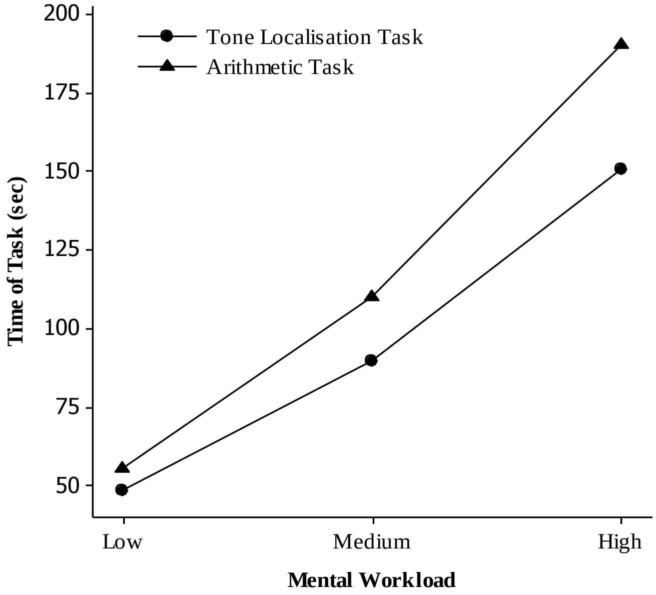


Figure 5.3 Cumulative time of task (sec) implies correlation the three levels of mental workload for both arithmetic and tone localisation tasks

5.2.4.2 Physiological Parameters

Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for both HR and HRV parameters ($p<0.05$). Participants' HR rose as the difficulty workload of both mental tasks increased and the repeated ANOVA results showed that the levels of difficulty of the auditory arithmetic and tone localisation task significantly affected the participants' HR ($F(1.4,18.9) = 68.06$, $p<0.01$). According to a repeated contrast test, a significant difference was observed between the low workload and the medium workload of the arithmetic test ($p<0.01$), and between the medium and high workloads ($p<0.01$) (Figure 5.4.) However, there was no significant impact from task type interaction and their workloads on HR ($F(1.3,13.9) = 0.499$, $p=0.13$).

Moreover, a repeated contrast test showed a significant difference between the low workload and the medium workload of the tone localisation task ($p<0.05$), and between the medium and high workloads ($p<0.01$). Finally, when the task workload (arithmetic and tone localisation) increased, HR rose. The effect of task type was significant on HR ($F(1,11) = 12.09$, $p<0.05$). According to a Tukey HSD test, the differences between the two tasks were observed at low, medium and high levels of mental workload ($p<0.05$ for all comparisons). See Figure 5.4.

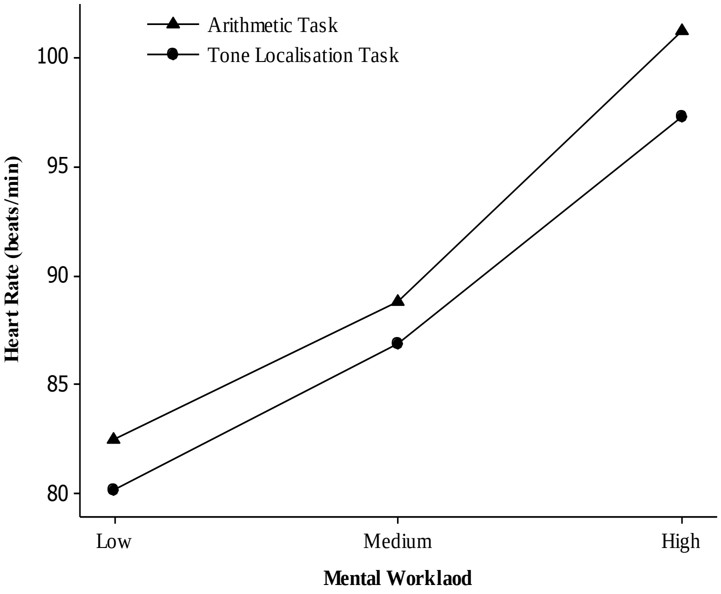


Figure 5.4 Mean heart rate (HR) implies correlation the three levels of mental workload of auditory arithmetic and tone localisation mental tasks

The ANOVA showed that the workloads of difficulty of the auditory arithmetic and tone localisation task significantly affected participants' HRV (*F*(1.2,13.4) = 50.28, *p*<0.01). However, no significant impact from task type interactions and their workloads was seen on HRV (*F*(1.23,13.8) = 0.847, *p*=0.86).

A repeated contrast test illustrated the significant difference between HRV at low workload and the medium workload of the arithmetic test (*p*<0.05), and between the medium and high workloads (*p*<0.05) (Figure 5.5). Moreover, a repeated contrast test showed a significant difference between the low workload and the medium workload of the tone localisation (*p*<0.01), and between the medium and high workloads (*p*<0.01). The effect of task type was significant on HRV (*F*(1,11) = 14.21, *p*<0.05). Furthermore, Tukey's HSD analysis showed significant differences between both auditory mental tasks at low, medium and high workloads (*p*<0.05 for all comparisons).

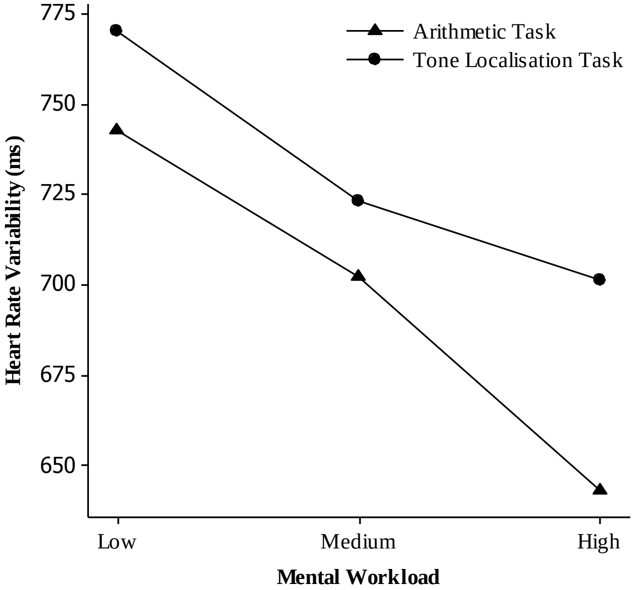


Figure 5.5 Mean HRV implies correlation the three levels of workload for both arithmetic and tone localisation mental tasks

5.2.4.3 NASA-TLX

Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was met for NASA-TLX score parameters (*p*>0.05).The impact of the arithmetic task and tone localisation task workloads on overall NASA-TLX ratings was significant (*F*(2,22) =645.86, *p*<0.01). A repeated contrast test showed that there was a significant difference between the low workload and the medium workload of the auditory arithmetic test (*p*<0.01), and between the medium and high workloads (*p*<0.01). As arithmetic and tone localisation mental workloads increased, the overall NASA-TLX scores also increased significantly (Figure 5.6.) However, no significant impact from task type interactions and their workloads on TLX was observed (*F*(2,22) = 1.04, *p*=0.435).

However, a significant difference was observed between the low workload and the medium workload of the tone localisation (*p*<0.01), and also between the medium and high workloads of tones task (*p*<0.05). The effect of task type was not significant (*F*(1,11) = 2.25, *p*=0.093).

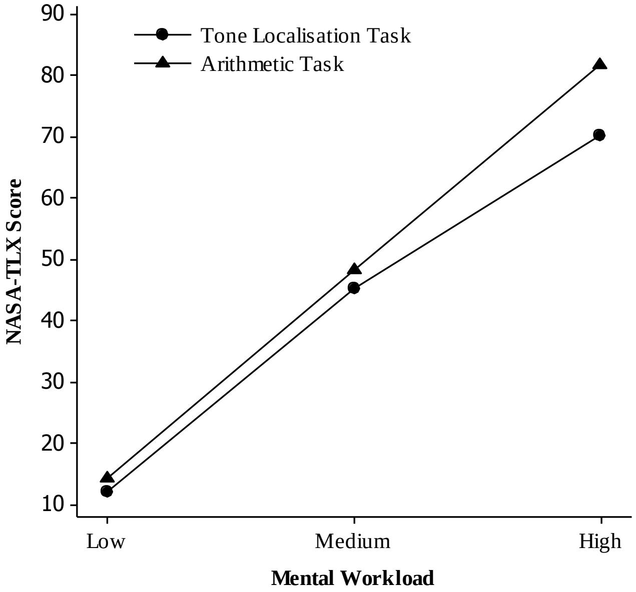


Figure 5.6 Mean NASA-TLX ratings implies correlation three levels of auditory arithmetic task and tone localisation task

5.2.5 Discussion

This pilot study was carried out to validate and verify the three difficulty workloads of two auditory tasks: the arithmetic task (auditory-verbal resource) and tone localisation task (auditory-spatial resource) to be used in the main experiment. Furthermore, according to the results there were no interactions between the two auditory tasks, so interaction effects will not impact on the results of the main experiment in this chapter. However, the performance analysis showed that increasing difficulty in both the arithmetic and tone localisation tasks led to a decrease in the accuracy of responses (i.e. error increasing). This is consistent with Lee (2001), who found that increasing the number of activated speakers in a tone identification task led to increased errors. In addition, Fredericks et al. (2005) pointed out that increasing the difficulty of a mental calculation and Stroop test task increased the mistakes of participants. In addition, the results of the present study illustrated that the time of task increased as the tone localisation and arithmetic task difficulty workload increased. Generally, the auditory-verbal resource was more difficult than the auditory-spatial resource, since the participants' time to achieve correct responses was greater in the arithmetic task. The performance analysis revealed a significant difference between low, medium and high workloads of both mental auditory tasks.

Heart rate and heart rate variability were sensitive to an increase in mental demand. HR rose significantly as the complexity of both tasks increased. This result was consistent with those of Audiffren et al. (2009), who found that HR increased more in an auditory random generator task than in a tone reaction time task. Moreover, the heart rate of participants during the arithmetic task was higher than during the tone localisation task; in other words, the arithmetic task was more stressful than the other task. This was consistent with the accuracy and time of task, which proved that the tone localisation task was easier than the arithmetic task. Furthermore, heart rate variability was affected by the mental workload under both tasks. HRV decreased as the tone localisation and arithmetic difficulty workloads were increased. These results were supported by Hwang et al. (2008), who concluded the participants' heart rates increased as the mental mathematical task levels increased during a secondary task in a control room environment. In addition, they observed a decrease in heart rate variability associated with increased mathematical task difficulties.

Finally, as expected, the NASA-TLX score was sensitive to increasing demand on the cognitive tasks. A high score was observed at the high workload of arithmetic and tone localisation tasks. Men scored lower than women in both tasks. The NASA-TLX showed there was a significant difference between the low, medium and high workloads of the auditory arithmetic and tone localisation tasks. This was similar to previous studies that have found a significant increase in NASA-TLX scores with increased workloads of auditory arithmetic tasks (DiDomenico and Nussbaum 2008), public speaking tasks (Fredericks et al., 2005) and sound localisation (McAnally and Martin, 2007).

In conclusion, the aim of this pilot study was achieved; the three complexity workloads for the two auditory mental tasks were validated. The three difficulty workloads of auditory arithmetic task were validated and no interactions were observed between the arithmetic and tone localisation tasks. The measures used in this study were sensitive to the difficulty workloads of both tasks. These measures were two objective measures using performance variables (accuracy and time of correct responses) and physiological variables (heart rate and heart rate variability). On the other hand, the NASA-TLX was used as a subjective assessment tool to reflect mental workload.

5.3 MAIN STUDY METHOD

5.3.1 Experimental Design

This study is divided into two experiments designed to address whether physical workload interacts with auditory verbal attentional resources (mental arithmetic-experiment 1) and/or auditory spatial resources (tone localisation- experiment 2). The first experiment examined the impact of physical and mental arithmetic task interaction on auditory attentional resources (verbal resources), while the second experiment tested the effect of physical and mental workload combination on spatial auditory attentional resources. The two experiments included interactions of physical workload (PWL) and mental workload (MWL) under three different conditions, as illustrated in Table 5.2. The hypotheses presented in the table below were derived from the literature review (see Chapter 2, section 2.8), and not from previous experimental results in this thesis. Repeated measures analysis was used for the *within-subjects factor* (three physical and mental workload levels of interactions) and *between-subjects factors* (types of auditory mental tasks (i.e. verbal and spatial tasks) and gender as mentioned in Chapter 3 (section 3.2.1).

Table 5.2 The nine conditions of interaction between physical load and mental auditory arithmetic and tone localisation tasks

		Mental Auditory Arithmetic Workload OR Tone Localisation Workload (MWL)		
		Low Mental Workload	Medium Mental Workload	High Mental Workload
Physical Workload (PWL)	Low load (20% Wmax)	Participants' performance will be worse	Participants' performance will be worse	Participants' performance will be worse
	Medium load (50% Wmax)	Participants' performance will be better	Best performance will occur under this condition	Participants' performance will be worse
	High load (80% Wmax)	Participants' performance will be worse	Participants' performance will be worse	Worst performance will occur under this condition

5.3.2 Experimental Tasks

- ***Auditory arithmetic task (auditory-verbal task)***

The arithmetic task was presented verbally and included three difficulty levels as mentioned previously in 5.2.1, and the validation of these levels was satisfied in the pilot study (section 5.2).

- ***Tone Localisation Task (auditory-spatial task*****)**

In the tone localisation task, participants were required to select the speaker that produced the pure tone, and three levels of difficulty were included, as mentioned previously in 5.2.1 and the validation of these levels was satisfied in the pilot study (see section 5.2).

- ***Physical Task***

The physical workloads were similar to those used in Chapter 4 with the same three levels of difficulty, a bicycle-ergometer (20, 50 and 80% of maximum workload capacity (Wmax)), as stated in Chapter 4 (section 4.2.2). These physical levels were used in order to satisfy the level of physical loads from low to difficult.

5.3.3 Outcome Measures

As mentioned in section 3.3.2, all outcome measures (i.e. dependent variables) were similar across all experimental studies. There were four main outcome measures: Performance (accuracy and time of task); physiological measures (HR, HRV and MBP); rSO2 (oxygenation changes in the brain, physiological measure); and subjective assessment tools (NASA-TLX, Borg-CR10 and Borg-RPE). Furthermore, the mental demand dimension (MD) and physical demand dimension (PD) in NASA-TLX analyses were presented as mentioned in Chapter 3 (see section 3.3.2).

5.3.4 Participants

Two groups of 15 females and males (aged 25–35) participated in the experiment. The first 15 subjects participated in the first experiment; physical workload vs. auditory-verbal mental task. The other 15 participants tookpart in the second experiment; physical workloads vs. auditory-spatial mental task (see details in Chapter 3, section 3.2.5). The statistical description of participant groups across the experiment is illustrated in Table 5.3. The statistics of physiological parameters for the participants are illustrated in Table 5.4. All participants reported that they had normal hearing on the normal hearing questionnaire soft version (a brief Self-Assessment of Communication, Schow and Nerbonne, 1982). In addition, the study was approved by the Brunel University Ethics Committee (see Appendix D).

Table 5.3 Statistical description of participants

Total participants	physical workload vs. verbal mental task(Gender)	physical workload vs. spatial mental task (Gender)	Age range	Male (Mean ± SD)	Female (Mean ± SD)
30	15 (M=8,F=7)	15 (M=8,F=7)	25 – 35	(28.5± 2.2)	(30.7 ± 3.1)

Table 5.4 Anthropometric, physiological parameters for sample size and maximum workload capacity (Mean±SD) in both mental auditory tasks

	Arithmetic(n=15)	**Tone Localisation(n=15)**
Variable	*Mean± SD*	*Mean± SD*
Age (years)	28.5± 3.16	29.70 ± 3.10
Height (cm)	175.0± 4.65	166.8 ± 5.34
Weight (kg)	77.22± 8.75	65.17± 7.20
HR at rest level (bpm)	85.73 ± 6.49	80.60 ± 9.60
MBP at rest (mmHg)	84.5 ± 4.16	79.90 ± 5.33
rSO2 at rest level (%)	63.34 ± 7.49	63.71 ± 9.50
Wmax (Watt)*	246 ± 29.70	198.0± 26.50

*Wmax: is the maximum workload capacity.

5.3.5 Materials and Equipment

As stated in Chapter 3, section 3.3.3, most of the equipment and materials across all experiments were similar; details of equipment used in this experiment were presented in section 3.3.3.

5.3.6 Procedure

Physical Workload vs. Auditory Arithmetic Mental Task

The arithmetic task experiment was divided into two visits. The aims of the first visit were to determine the maximum physical workload capacity for each participant and to conduct a practice session for the experiments.

During the first visit, participants were given a brief introduction to the experiment and a health questionnaire (see Appendix B) before they started. They were provided with instructions and advised on how to perform the cycling and auditory arithmetic (verbal load), which they were able to practise during the practice session in order to become familiar with the steps involved. Then they performed the identical procedure for maximum workload capacity measurements to that presented in section 4.3.6. The information sheet (see Appendix D) and informed consent were obtained before their participation in the experiments (see Appendix F).

On their second visit, participants were asked to affix physiological monitors similarly to the description in section 4.3.6. The experiment began, and the condition was selected randomly in order to reduce potential practise effects and fatigue related to the order of these conditions. The participants started pedalling, and the arithmetic test was presented aurally similarly to the procedures mentioned in section 5.2.3. Participants responded by pressing the answer on the number keyboard on the front of the bicycle. Each participant completed 25 arithmetic questions within each condition as accurately and quickly as possible in the allotted six minutes. The next set of numbers was presented immediately following a response, whether correct or incorrect. The arithmetic task continued until the end of the task. The time allotted for the task was sufficient for all participants. The time of each condition was fixed, and the presentation speed of the mental arithmetic problem was related to the ability of each participant. The number of correct responses and the actual time required to complete the section was recorded by the software. After each trial, the volunteers rested for five minutes until their heart rates reached resting levels. Immediately after completing each trial, participants were asked to complete the Borg-CR10 and RPE (see Appendix H) during the rest period between each level. In addition, the NASA-TLX scale (see Appendix G) was completed in order to measure mental workload and overall workload.

Physical Workload vs. Tone Localisation Task

The second experiment (tone localisation task) included two visits and was essentially identical to the previous experiment. The aim of this study was to investigate the effects of physical and mental demands on auditory-spatial resources. The procedures of the first experiment were then implemented, and all measurements were recorded. The speakers were placed in the room in the positions described earlier and were assigned a number. Participants were placed in the centre of the experiment room, which had the dimensions 3.30 m × 3.0 m × 2.68 m. For details of sound specification in the room see Chapter 3, section 3.2.3. Then the participant started pedalling and the pure tone and white noise were generated simultaneously, similar to the procedures in section 5.2.3. Two sounds were presented concurrently from two different speakers. The participant responded to the pure tone by pressing the number of the speaker on the small keyboard on the front of the cycle ergometer, which was connected to the computer. For example, if the tone sounded from speaker 3, the participant pressed number 3 on the keypad. Each participant completed 25 trials within each condition as accurately and quickly as possible in the allotted six minutes. Also, all the subjective assessment ratings were completed in rest time, similar to previous experiment procedures.

5.4 RESULTS

The descriptive statistics (mean ± standard deviation) for all measures (accuracy, time of task, HR, HRV, MBP, rSO2, Borg-CR10, Borg-RPE and NASA-TLX scores) across all nine physical and mental workload interaction conditions are illustrated in Appendix I.

5.4.1 Performance

Participants' performance was measured by recording the accuracy and time of task (cumulative time). Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for both accuracy and time of task ($p<0.05$), so the F-adjusted was used.

Accuracy

The repeated ANOVA outputs showed that the impact of physical workload levels was significant ($F(1.9,51.5) = 91.49$, $p<0.01$). Furthermore, participants' accuracy was significantly influenced by mental workload levels ($F(1.8,49.1) = 89.49$, $p<0.01$). The effects of physical × mental workload interaction factors were significant on accuracy ($F(2.7,70.9) = 17.24$, $p<0.05$). However, the better accuracy appeared at the low and medium levels of physical workload (20 and 50% Wmax) versus low mental workload for both auditory tasks. The overload of physical (80% Wmax) and mental auditory demand interactions led to the worst accuracy. Interestingly, a medium level of physical workload improved information processing since better accuracy occurred at a low mental workload for both auditory mental tasks, the arithmetic and tone localisation tasks (see Figure 5.7)

Now the differences between these levels of physical and mental workload will be presented. According to the contrast analysis, a significant difference was observed between all levels of physical workload ($p<0.05$), except between low and medium physical loads at low mental demands in both arithmetic and tone localisation ($p=0.061$ and $p=0.073$, respectively). That means medium physical workload leaded to better accuracy at low mental workload. Additionally, the analysis revealed a significant difference between mental workload levels, low workload vs. medium workload and medium level vs. high workload in both tasks, ($p<0.05$ and $p<0.01$). The results showed that the impact of task type on accuracy was not significant ($F(1,26) = 1.38$, $p=0.251$).

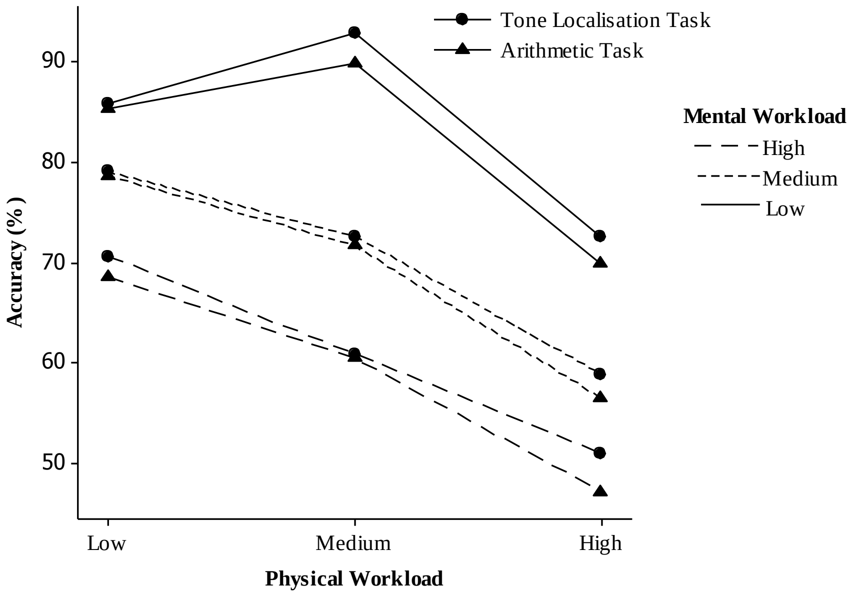


Figure 5.7 Mean of participants' accuracy percentage of tone localisation and arithmetic auditory tasks responses against physical and mental workload interaction

Time of Task (Cumulative Time of Task)

The ANOVA technique showed that mental workload significantly influenced participants' time of task ($F(1.6,42.6) = 3993.82$, $p<0.01$). In addition, the physical workload factor significantly impacted on participants' time to of task ($F(1.9,49.8) = 754.21$, $p<0.01$). Moreover, the effects of physical and mental workload interactions on time of task were significant ($F(2.9,74.7) = 77.61$, $p<0.05$). In addition, when the task workloads (arithmetic and tone localisation) increased, the cumulative time of task increased, except for the time of task at a medium level of physical workload, as shown in Figure 5.8. The results showed that a low physical workload (20% Wmax) led to better time of task at medium mental workloads in both auditory tasks. In contrast, a medium physical workload level (50% Wmax) led to better task time at low mental demand in both tasks. However, the worst time was observed in both tasks with overload conditions of workload interactions (see Figure 5.8).

The contrast analysis illustrates that there is a significant difference between the physical workloads in both tasks under all workloads of interaction ($p<0.05$), except for low and medium physical workload vs. low mental workload interactions in tone localisation and arithmetic tasks ($p=0.058$ and $p=0.062$ respectively). However, the analysis revealed a significant difference between mental workload levels at all workloads of interaction ($p<0.05$) except at the low physical load (20% Wmax), where there were no significant differences between low and medium mental workloads in both arithmetic and tone localisation tasks ($p=0.082$ and $p=0.073$, respectively).The impact of task type was significant on time of task ($F(1,26) = 13.08$, $p<0.05$). Generally, the arithmetic task needed more time than the tone localisation task. According to Tukey's HSD test, a significant difference occurred between tasks at high physical load × medium mental workload ($p<0.05$) and high physical load × high mental workload ($p<0.05$). In contrast, there was no significant difference between tasks under other workload interactions ($p>0.05$).

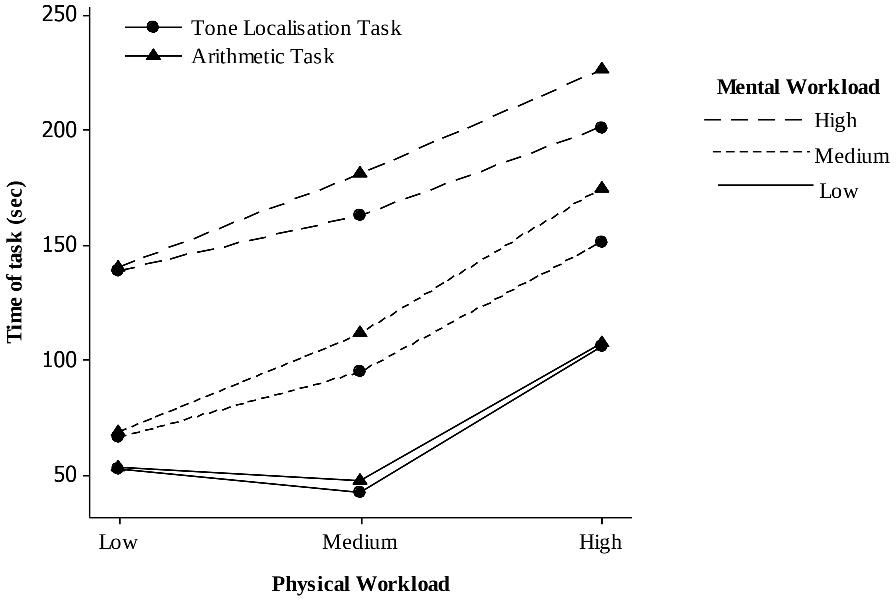


Figure 5.8 Mean of task time of both auditory tasks against workload interactions

Gender Differences and Performance (Accuracy and Time of Task)

The results showed that the effects of gender on accuracy were not significant ($F(1,26) = 1.78$, $p=0.210$). However, the influence of gender on time of task was significant ($F(1,26) = 22.03$, $p<0.05$). Generally, the task time for females was higher than males in arithmetic and tone localisation auditory tasks. However, Tukey's HSD test found that there was no significance between males and females in either task's interactions with physical workload ($p>0.05$), with the exception of the arithmetic task at a high physical workload vs. medium mental load ($p<0.05$), a medium physical workload vs. high mental load (p<0.05) and high physical loads vs. high mental load (p<0.05). (See Figure 5.9).

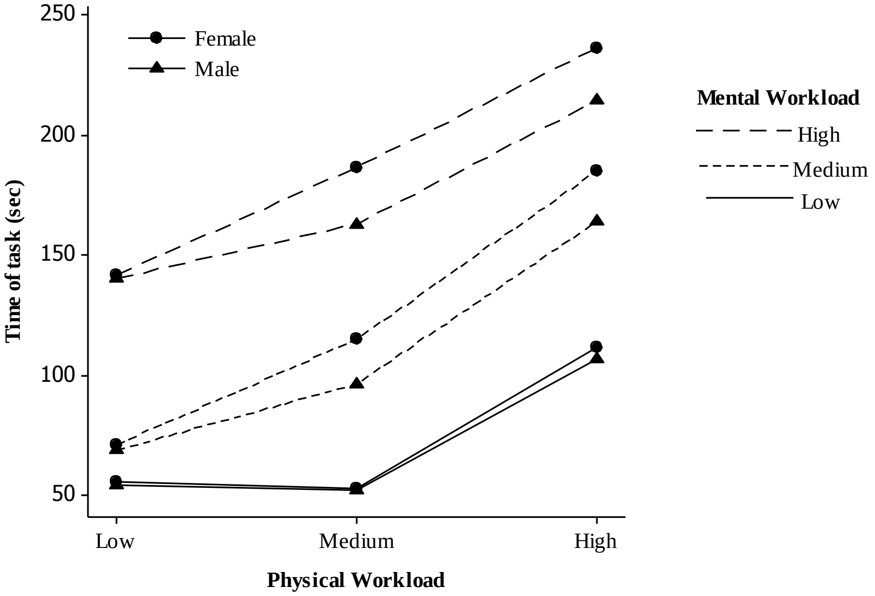


Figure 5.9 Mean of task time for males and females in the auditory arithmetic task during physical and mental workload interaction

5.4.2 Physiological Parameters

Four main physiological measurements were used to reflect the impact of physical and mental workload interactions on auditory attentional resource performance. In addition, they were used to reflect physiological arousal due to physical and mental workload. The measurements used were physiological indicators that included HR, HRV and MBP; brain activity was measured by rSO2. Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for HR, HRV and MBP (p<0.05), so the F-adjusted was used; it met for the rSO2 measure (p>0.05).

Heart Rate (HR)

Mental workload had a significant impact on participants' HR (F(1.8,46.7) = 2296.12, p<0.01) in both tasks. Furthermore, physical workload levels in both auditory tasks significantly affected participants' HR (F(1.6,41.5) = 900.51, p<0.01). Generally, the HR mean significantly increased as physical and mental workload increased (Figure 5.10). Moreover, a significant interaction between physical and mental workload was found for HR (*F*(2.1,55.6) = 22.55, *p*<0.05). Tukey's HSD post-hoc test showed that at a high workload of mental workload versus high physical loads, the arithmetic task led to higher HR (*p*<0.05).

According to contrast analyses, significant differences were found between HRs in physical workload (*p*<0.01 and *p*<0.01) for a low physical workload vs. medium workload and medium vs. high workload, respectively. However, the analysis indicated significant differences between mental workload levels under all workloads of interaction (*p*<0.05), except at low physical load (20% Wmax) in the tone localisation task where there were no significant differences between low and medium mental workloads (*p*=0.068). The impact of task type was not significant (*F*(1,26) = 2.61, *p*=0.092).

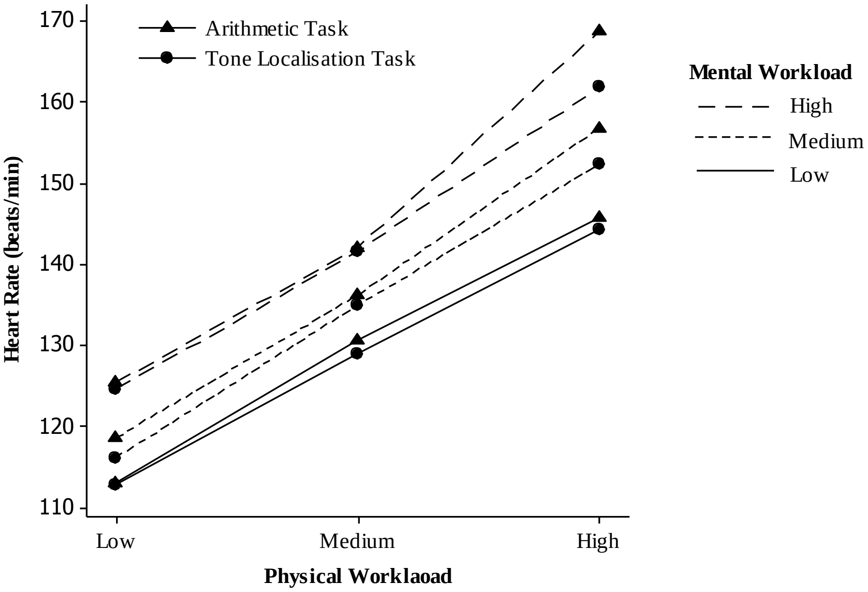


Figure 5.10 Mean HR for arithmetic and tone localisation tasks under nine levels of physical and mental workload interaction

Heart Rate Variability (HRV)

There was a significant impact of mental workload levels in both auditory tasks (arithmetic and tone localisation) on participants' HRV (*F*(1.6,42.5) = 317.89, *p*<0.01). Furthermore, physical workload levels significantly affected participants' HRV (*F*(1.7,44.6) = 41.49, *p*<0.01). Moreover, the physical and mental workload interaction had a significant influence on HRV (*F*(2.5,65.2) = 39.69, *p*<0.05). Mean

HRV decreased as mental workload increased in both tasks, whereas it increased as physical workload increased (Figure 5.11).

The repeated contrast tests showed that there was a significant difference between all physical levels in both tasks (*p*<0.05 for both), except between HRV at medium and high physical loads and at high mental workload in the arithmetic task (*p*= 0.086). Also, there was a significant difference between mental workload levels, low workload vs. medium workload was (*p*<0.05) and between medium workload vs. high workload was (*p*<0.05) in both tasks.

The impact of task type on HRV was significant (*F*(1,26) = 13.19, *p*<0.05). Lower mean HRV was observed in the auditory arithmetic task compared to the tone localisation task when carried out with a physical workload. However, Tukey's test revealed significant differences in HRV for both auditory tasks during high physical workload × medium mental workload (*p*<0.05) and during high physical workload × high mental workload (*p*<0.05). However, there were no significant differences in either task under other workload interactions (*p*>0.05).

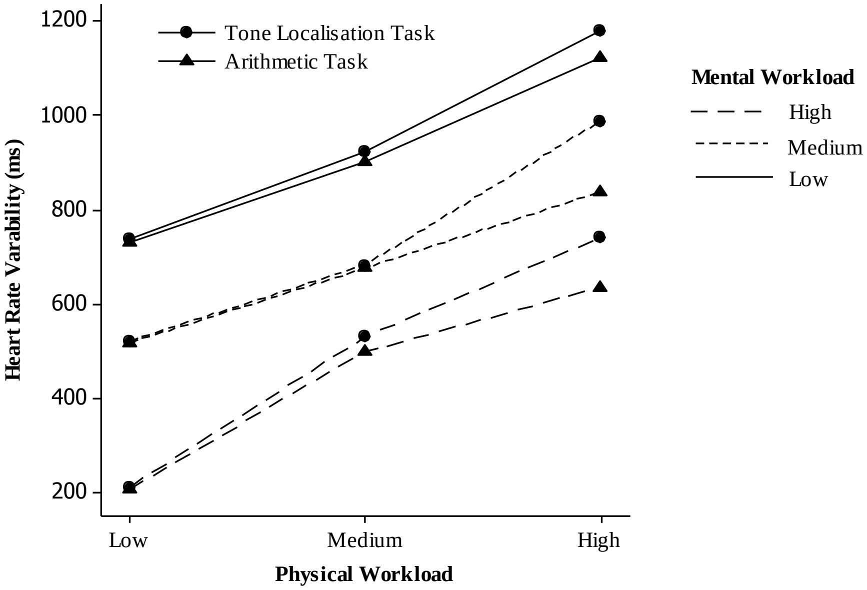


Figure 5.11 Mean HRV for both auditory tasks against workload interactions

Mean Blood Pressure (MBP)

The repeated ANOVA test showed that mental workload had a significant impact on participants' mean blood pressure (*F*(1.8,47.2) = 112.39, *p*<0.01). In addition, physical workload had a significant impact on participants' mean blood pressure in both tasks (*F*(1.9,49.4) = 801.59, *p*<0.01). Moreover, the effects of physical and mental workload interactions on MBP was significant (*F*(4,104) = 4.94, *p*<0.05). Tukey's HSD analysis indicated that at a high workload of mental workload versus medium and high physical loads (*p*<0.05 for both), and at a medium physical load versus high mental load (*p*<0.05), the arithmetic task showed a higher MBP (Figure 5.12).

The repeated contrast tests showed that there were significant differences between all physical levels under all workload interaction conditions (*p*<0.05) in both auditory tasks, except in the tone localisation task where there was no significant difference between MBPs at low and medium physical loads versus high mental workload (*p*=0.067). Furthermore, there were significant differences between all mental workloads under all workload interactions (*p*<0.05) in both auditory tasks.

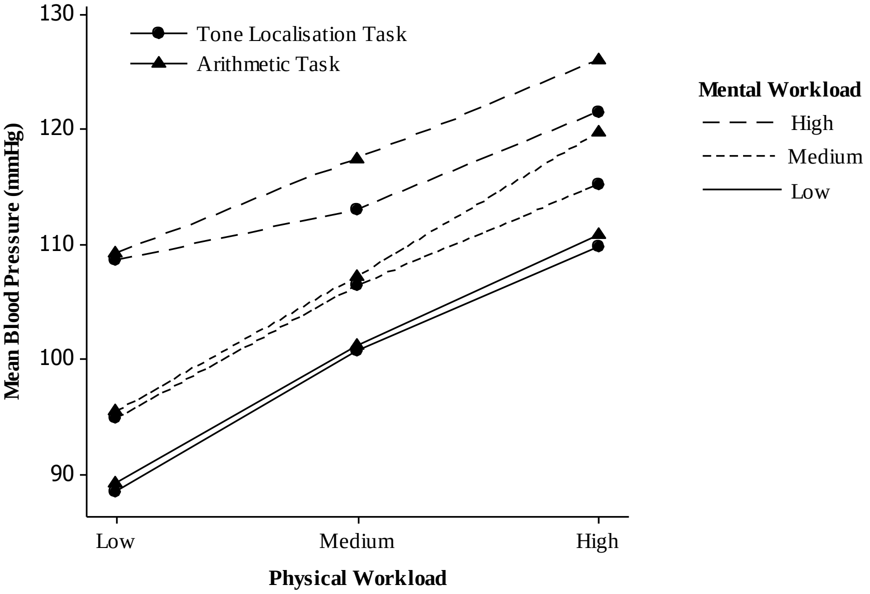


Figure 5.12 Mean blood pressure for both auditory tasks against workload interactions

The variance analysis showed that the effects of type of task (arithmetic or tone localisation) on MBP was not significant (*F*(1,26) = 1.13, *p*=0.298).

Gender Differences and Physiological Parameters

In the gender analysis, the ANOVA showed that gender had a significant impact on HR (*F*(1,26) = 14.82, $p<0.05$). Tukey's analysis showed no significant differences in HR between males and females in the tone localisation task under all levels of workload interactions ($p>0.05$). In contrast, there was a significant difference between genders in the auditory arithmetic task at a high level of physical workload × medium mental workload ($p<0.05$) and high level of physical workload × high mental workload ($p<0.05$). Generally, the female HR mean was higher than the male under all conditions of workload interaction in both mental tasks. (See Figure 5.13).

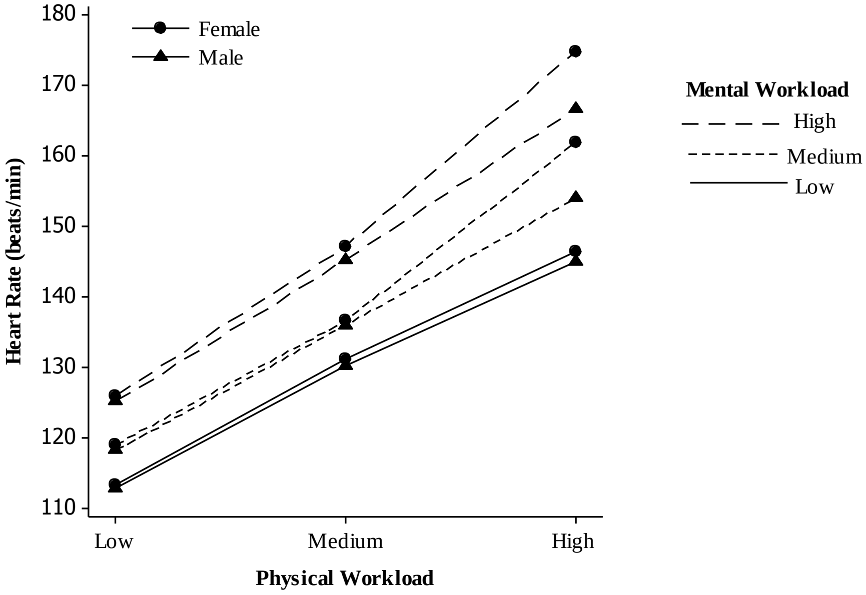


Figure 5.13 Mean HR for males and females in the auditory arithmetic task during physical and mental workload interaction

However, the ANOVA found that gender was not significant on HRV (*F*(1,26) = 1.5, $p=0.623$). The between-subjects factor test (ANOVA) displayed that the impact of gender was significant on MBP (*F*(1,26 = 9.03, $p<0.05$). In addition, there was a significant difference between genders in the auditory arithmetic task at a medium level of physical workload (50% Wmax) × high mental level ($p<0.05$), a high level of physical workload × medium mental level ($p<0.05$) and a high level of physical workload × high mental workload ($p<0.05$). (See Figure 5.14). In contrast, there was no significant difference between genders in the tone localisation task among workload interactions at any condition ($p>0.05$).

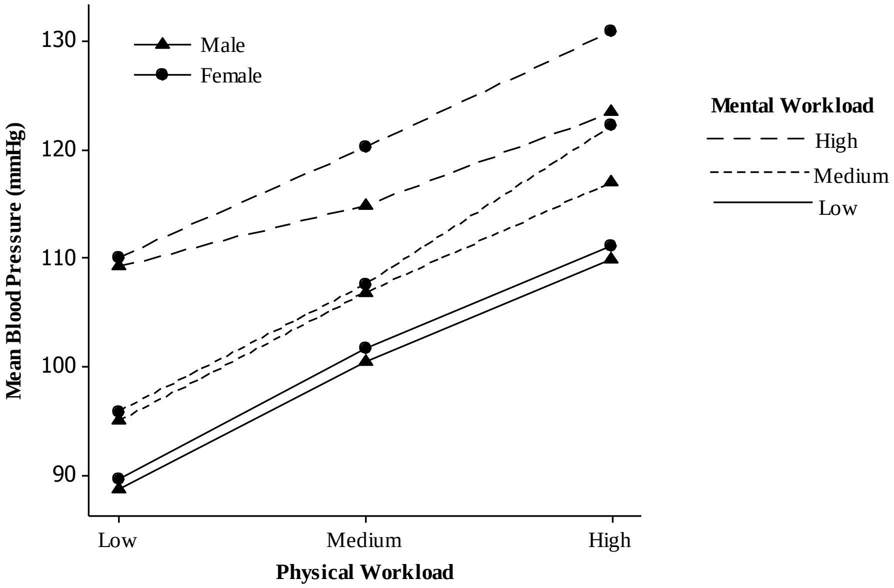


Figure 5.14 Mean BP for males and females in the auditory arithmetic task during physical and mental workload interaction

5.4.3 Brain Activity versus Physical and Mental Workload Interaction

Regional Cerebral Oxygen Saturation (rSO2)

According to the analysis, there was a significant impact of mental workload on the percentage of oxygen in the brain (rSO2) ($F(2,52) = 864.7$, $p<0.01$) in both tasks. Physical workload levels in both auditory tasks also had a significant effect on rSO2 of participants ($F(2,52) = 498.33$, $p<0.01$). Moreover, the physical and mental workload interactions had a significant influence on rSO2 ($F(4,104) = 17.7$, $p<0.05$). Generally, the rSO2 mean significantly increased while mental workload increased, whereas it decreased significantly while physical loads increased (Figure 5.15). Tukey's HSD analysis indicated that the auditory arithmetic task resulted in a higher rSO2 mean than the tone localisation task at a high mental workload vs. three physical loads levels ($p<0.05$) and at a medium mental load vs. high physical load ($p<0.05$).

According to the contrast analysis for rSO2, there was a significant difference between mental workload levels in both mental tasks ($p<0.05$). Also, the data demonstrated significant differences between rSO2 under all physical workload levels ($p<0.05$), except between medium and high physical loads at a high mental load in the arithmetic and tone localisation tasks ($p=0.074$ and $p=0.066$, respectively). However, the impact of task types on rSO2 was not significant (*F*(1,26) = 3.62, *p*=0.091).

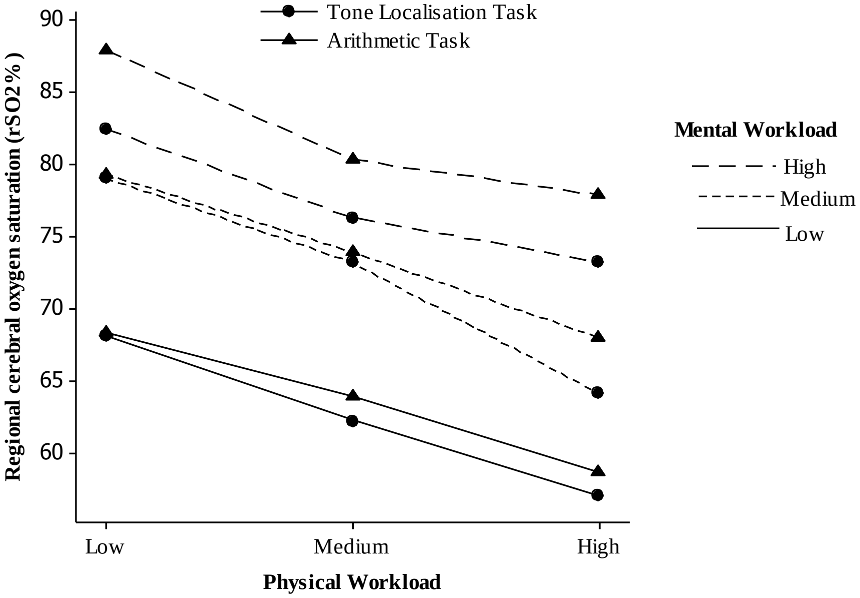


Figure 5.15 Mean of regional oxygen saturation in the brain for both auditory tasks responses against physical and mental workload interactions

Gender Differences and rSO2

The gender variable was not significant (*F*(1,26) = 2.7, *p*=0.114).

5.4.4 Subjective Assessment Tools

Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for Borg's scales (CR10 and RPE) and NASA-TLX scale ($p<0.05$), so the *F*-adjusted was used.

Physical Workload Assessment Tools

The Borg CR10 and RPE scales were used to evaluate subjective physical demand in the experiments. The scores significantly increased when physical workload increased. In addition, the effect of physical workload on the Borg-CR10 and RPE was significant (*F*(1.7,44.6) = 1213.76, $p<0.01$ and *F*(1.5,38.5) = 633.31, $p<0.01$, respectively). In contrast, the effect of mental workload on Borg scores was not significant (Borg-CR10, *F*(1.6,38.7) = 2.32, *p*=0.201 and RPE, *F*(1.7,44.2) = 1.03, *p*=0.61) (Figures 5.16 and 5.17). The interaction of physical and mental workload was not significant on either scale ($p>0.05$). The effect of task type factor on the Borg scores (CR10 and RPE) was also not significant (*F*(1,26) = 9.32, *p*=0.64 and (*F*(1,26) = 10.13, *p*=0.71), respectively. According to contrast analysis for the Borg-CR10, there was a significant difference between the physical workload levels in both tasks (*p*<0.01). In contrast, there were no significant differences between Borg-CR10 score and RPE score in mental workload levels in either auditory task (*p*>0.05).

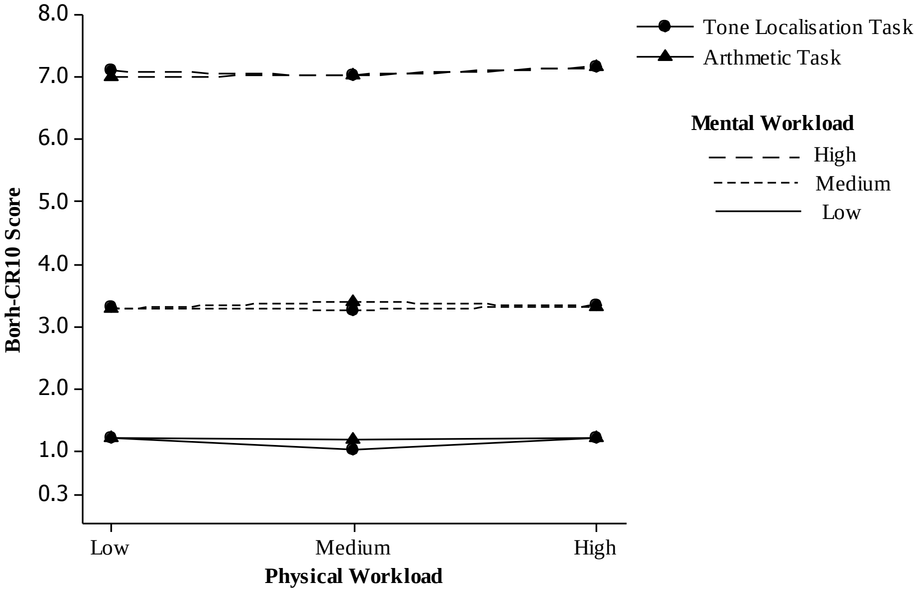


Figure 5.16 Mean Borg-CR10 scores for arithmetic and tone localisation mental tasks against physical and mental workload interaction

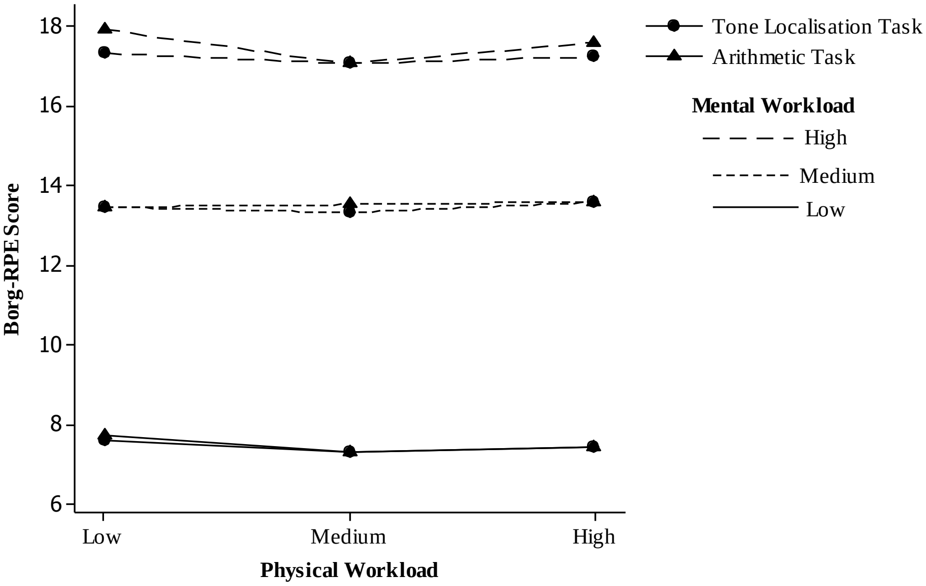


Figure 5.17 Mean RPE rating scores for arithmetic and tone localisation mental tasks against physical and mental workload interaction

NASA-TLX Assessment Tool

Overall mental workload on the TLX was calculated by averaging all the dimensions of the NASA-TLX ratings as noted in Chapter 4, section 4.4.4.

The ANOVA showed that NASA-TLX scores were significantly impacted by mental workload ($F(2,54) = 6643.11$, $p<0.01$). In addition, physical workload had a significant impact on TLX ratings ($F(1.7,44.5) = 4426.14$, $p<0.01$). The effects of the physical and mental workload interaction on NASA-TLX were not significant ($F(3.6,70.8) = 2.03$, $p=0.154$). In addition, when the task level (arithmetic or tone localisation) interaction with physical workload increased, the NASA-TLX rating increased (Figure 5.18). The impact of type of task was not significant ($F(1,26) = 2.38$, $p=0.091$).

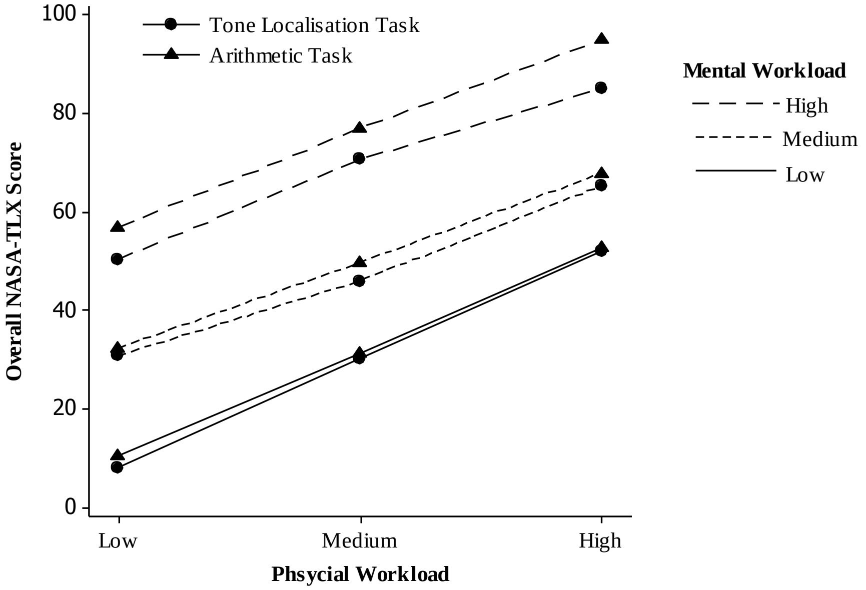


Figure 5.18 Overall NASA-TLX score implies correlation with physical and mental workload interactions for arithmetic and tone localisation tasks

According to contrast analysis for the NASA-TLX ratings, there was a significant difference between the mental workload levels ($p<0.01$) among all levels of workload interaction conditions. In addition, the analysis found significant differences between NASA-TLX scores in physical workload ($p<0.05$) among all levels of workload interaction.

As mentioned previously, in section 3.3.2, the effect of physical and mental workload levels on the mental demand dimension and physical demand subscale in the NASA-TLX was presented in the analysis in order to determine the importance of physical workload on the subjective mental demand dimension.

In terms of the mental demand dimension (MD) in the TLX, the ANOVA analysis showed that the mental workload of both tasks had a significant impact on the NASA-TLX rating ($F(1.8,46.7) = 721.45$, $p<0.01$). However, the impact of physical load on the MD dimension was not significant ($F(1.7,44.5) = 3.17$, $p=0.18$). The effect of physical and workload interactions was not significant either ($F(3.4,90.6) = 1.72$, $p=0.84$). The TLX score increased significantly as the levels of difficulty increased (Figure 5.19). The contrast test showed that there was a significant difference between all levels of mental workload in both tasks ($p<0.05$ for both). However, there were no significant differences between all levels of physical workloads ($p>0.05$). The effect of task type factor on the mental subscale was not significant ($F(1,26) = 0.99$, $p=0.342$).

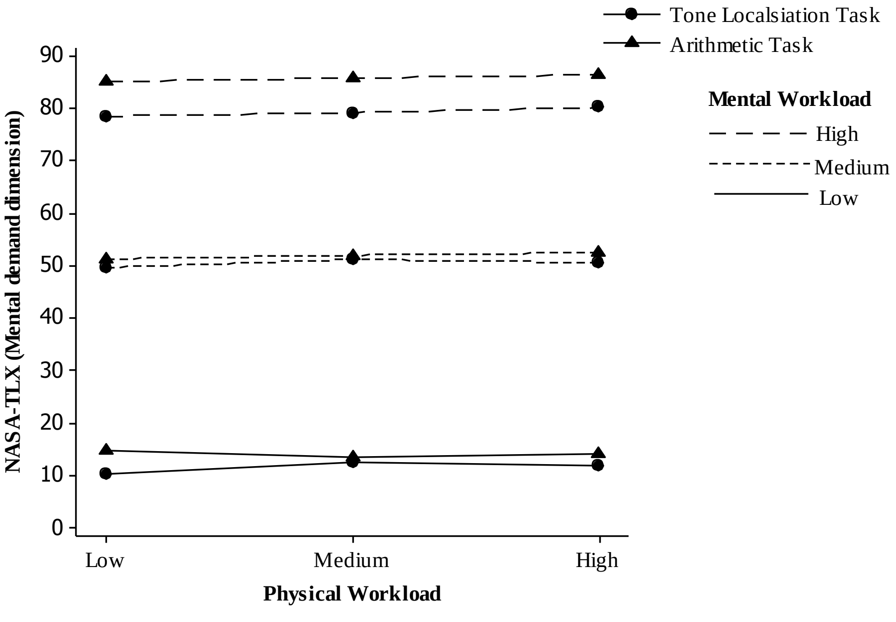


Figure 5.19 Mental demand dimension in NASA-TLX assessment scores for arithmetic and tone localisation tasks

In terms of the physical demand dimension (PD), the ANOVA showed that physical workload impacted significantly on the physical dimension of both tasks in NASA-

TLX rating (*F*(1.8,46.6) = 934.18, $p<0.01$), (Figure 5.20). However, the impact of mental loads on the physical dimension was not significant (*F*(1.7,44.6) = 2.25, $p=0.601$). The effect of physical and mental workload interactions was not significant (*F*(3.5,90.6) = 0. 57, $p=0.14$). The contrast test showed that there was a significant difference between physical workload levels under all levels of interaction, ($p<0.05$). In contrast, there were no significant differences between all levels of mental workloads ($p>0.05$).

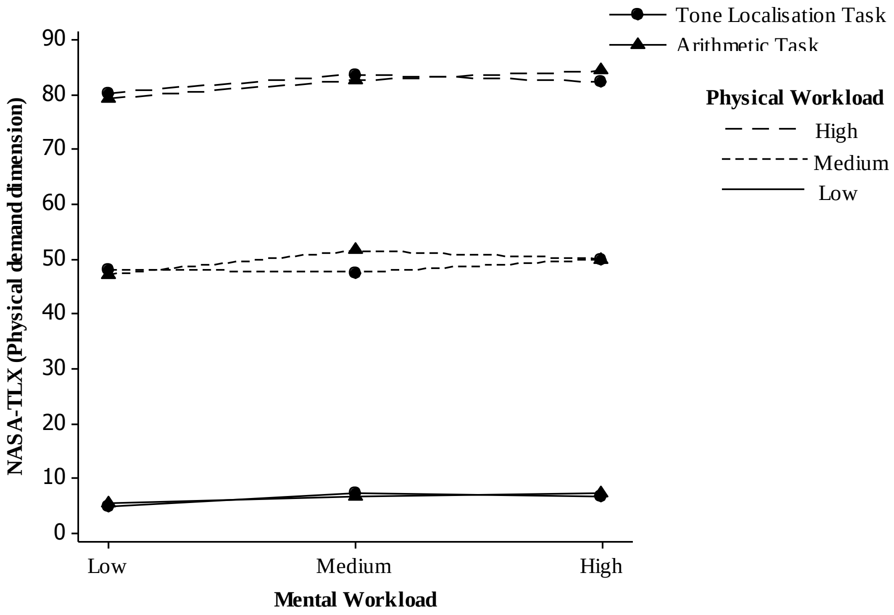


Figure 5.20 NASA-TLX physical demand dimension for arithmetic and tone localisation tasks

Gender Differences and Subjective Assessment Tools

The impact of gender on ratings in the CR10 and RPE scales was significant ($p<0.05$ and $p<0.05$). Generally, females scored higher in both Borg's scores than males. Furthermore, similar to the results in Chapter 4, Tukey's analysis showed that females scored higher than males in both Borg's ratings at a high level of physical workload (80% Wmax) versus low, medium and high mental workloads conditions ($p<0.05$) (Figure 5.21 and Figure 5.22) In addition, in the tone localisation task, the same differences between genders occurred at high levels of physical load in both the CR10 and RPE scores ($p<0.05$ for both).

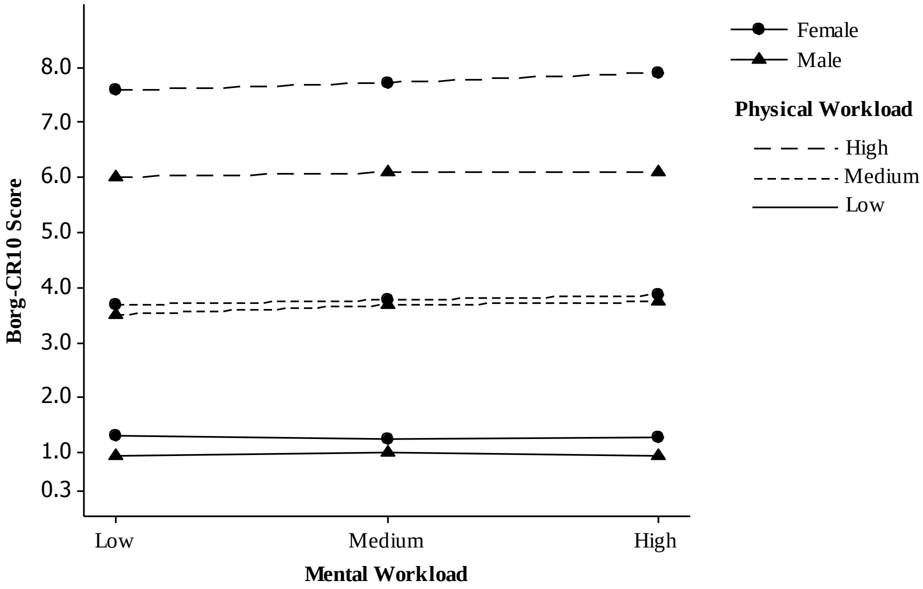


Figure 5.21 Mean Borg-CR10 scores for males and females in auditory arithmetic task during physical and mental workload interaction

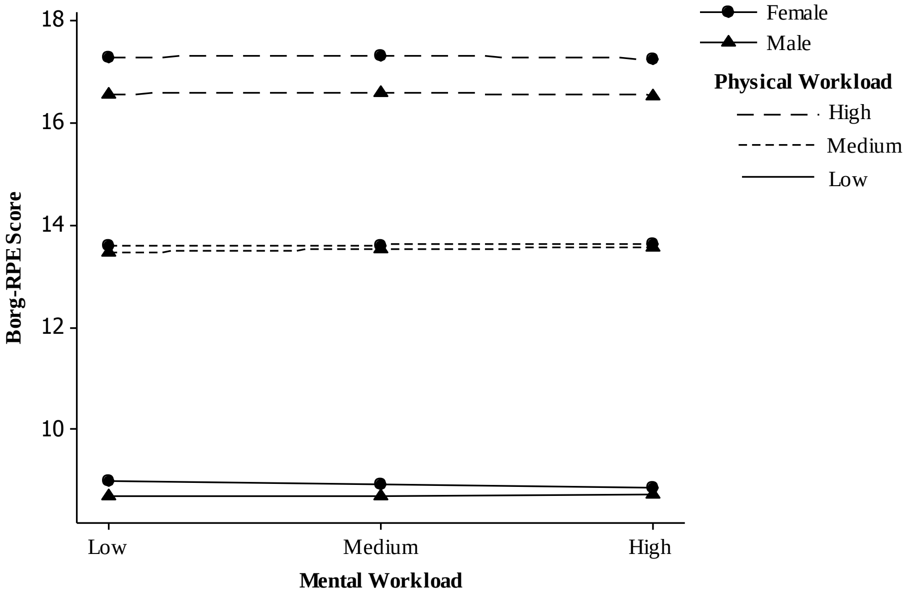


Figure 5.22 Mean Borg-RPE scores for males and females in auditory arithmetic task during physical and mental workload interaction

In the overall NASA-TLX score, the effect of gender was not significant ($F(1,26) = 1.43$, p=0.102). There was no significant difference between males and females in either task at any workload (p>0.05). In terms of the NASA-TLX and gender differences, the effect of gender was not significant (p=0.112). Also, the impact of gender on mental and physical dimensions was not significant ($F(1,26) = 1.79$, p=0.132) and ($F(1,26) = 2.34$, p=0.085).

5.4.5 Correlation between Objective and Subjective Variables

Pearson's correlation (r) was used to classify the relationship between the objective measures and subjective measures of physical and mental workload interactions for the arithmetic and tone localisation tasks, as illustrated in Table 5.5. This correlation was used to find out how the performance variables related to the physiological measures (i.e. positive or negative correlation, in particular for the rSO2 variable and how it related to NASA-TLX and Borg's scales.) Generally, the objective variables significantly correlated with overall NASA-TLX scores in both tasks. Moreover, HR and MBP strongly correlated with Borg-CR10. An interesting result is that rSO2 (oxygenation changes in the brain) significantly correlated with HR, MBP, time and NASA-TLX rating ($r = -0.42$, $p<0.05$; $r = -0.39$, $p<0.05$; $r = -0.43$, $p<0.05$; and $r = -0.39$, $p<0.05$ respectively.) Performance (accuracy) was significantly negatively correlated to the HR and MBP ($p< 0.01$).

Table 5.5 Pearson's correlation coefficient matrix (r) for the objective and subjective variables of mental workload (arithmetic and tone localisation tasks) and physical workload interactions

Variables		HRV	MBP	rSO2	Time	Accuracy	NASA-TLX scores	Borg-RPE	Borg CR-10 scores
HR		**-0.55**	**0.46**	**-0.42**	**0.35**	**-0.50**	**0.39**	**0.34**	**0.37**
	p-value	**0.01**	**0.01**	**0.01**	**0.03**	**0.01**	**0.02**	**0.02**	**0.02**
HRV			**0.42**	0.01	0.07	0.10	**-0.34**	0.17	0.20
	p-value		**0.01**	0.48	0.36	0.31	**0.03**	0.18	0.15
MBP				**-0.39**	**0.34**	**-0.55**	**0.59**	**0.40**	**0.39**
	p-value			**0.02**	**0.03**	**0.01**	**0.01**	**0.02**	**0.02**
rSO2					**-0.43**	-0.25	**-0.39**	0.30	0.29
	pvalue				**0.01**	0.09	**0.02**	0.06	0.06
Time						-0.20	**0.36**	0.11	0.01
	p-value					0.15	**0.02**	0.29	0.47
Accuracy							**-0.34**	**-0.32**	**-0.36**
	p-value						**0.03**	**0.04**	**0.02**
NASA-TLX scores								**0.34**	**0.38**
	p-value							**0.04**	**0.02**
RPE									**0.50**
	p-value								**0.01**

***bold represents the significance value $p< 0.05$**

5.4.6 Main Findings

Table 5.6 Main Results of the Second Experiment

Hypotheses	Results
1- The participants' best performance will occur at medium physical workload × medium auditory mental (verbal and spatial) workload interactions.	Accuracy and time of task significantly worsened ($p<0.05$) at medium levels of physical and mental workload interactions in both mental auditory tasks. *The hypothesis was rejected.*
2- The participants' worst performance will occur with high physical workload and high auditory mental workload interactions due to the high level of arousal.	In auditory mental tasks (arithmetic and tone localisation tasks), the significantly worst accuracy and time of task were observed ($p<0.05$). The hypothesis was not rejected.
3- Participants will perform better at medium physical workload × low auditory mental (verbal and spatial) workload interactions due to an increased level of arousal by physical workload.	The performance (accuracy and time of task) was significantly better ($p<0.05$) at a medium physical workload (50% Wmax) and low auditory mental workload. *The hypothesis was not rejected.*
4- Participants' performance will be worse with low physical workload × low auditory mental workload interactions due to a low level of arousal.	Performance was better in both auditory mental task conditions at low physical workload × low auditory mental workload interactions ($p<0.05$). *The hypothesis was rejected.*
5- The participants' best performance will occur with medium physical workload × low visual mental workload. The Participants' will perform better with a medium physical workload × low visual mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.	The performance (accuracy and time of task) significantly worsened ($p<0.05$) at a medium physical workload (50% Wmax) and medium mental workload but was better at medium physical workload and low mental workload. Increasing levels of physical workloads significantly increased the oxygen delivered to the brain by reducing rSO2 (percentage of oxygenation changes) ($p<0.05$). *The hypothesis was rejected for performance at medium workload interactions but was not rejected for other condition.*
6- The worst performance will occur with high physical workload and high auditory mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high auditory workload since the increasing level of auditory mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the auditory workload.	The performance worsened at high physical load × high auditory mental workload interactions because of the reduction in brain oxygen since rSO2 was significantly increased at a high auditory workload ($p<0.05$). Moreover, there was no significant decrease in rSO2 at medium and high physical levels under medium and high mental workloads in either task type ($p<0.05$). *The hypothesis was not rejected.*
7- No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level caused by the physical activity and increased oxygen delivered to the brain.	There were no significant differences between the genders in the accuracy of auditory tasks. Females spent more time than males in arithmetic tasks at high physical and medium mental workloads ($p<0.05$). *The hypothesis was rejected for accuracy but was not rejected for time of task in the arithmetic task at the medium mental workload.*
8-At high levels of physical and mental workload combinations, men are expected to perform better than women in the auditory-spatial task, whereas women will perform better in the auditory-verbal task due to the physical workload capacity differences between the genders and the high level of arousal.	No gender differences were observed in the tone localisation task. Females spent more time than males in arithmetic tasks at high physical and medium mental workload ($p<0.05$). Gender differences appeared in HR and MBP at high level of physical workload interaction with mental workloads in the arithmetic task. *The hypothesis was rejected.*

5.5 DISCUSSION

As stated in section 5.1, the hypotheses of this chapter were sequenced as follows:

1. *The participants' best performance will occur at medium physical workload × medium auditory mental (verbal and spatial) workload interactions.*
2. *The participants' worst performance will occur with a high physical workload and high auditory mental workload interactions due to the high level of arousal.*
3. *Participants will perform better at medium physical workload × low auditory mental (verbal and spatial) workload interactions due to an increased level of arousal by physical workload.*
4. *Participants' performance will be worse with low physical workload × low auditory mental workload interactions due to a low level of arousal.*
5. *The participants' best performance will occur with medium physical workload × low auditory mental workload. The participants will perform better with medium physical workload × medium auditory mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of the physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.*
6. *The participants' worst performance will occur with high physical workload and high auditory mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high auditory workload since the increasing level of auditory mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the auditory workload.*

The current chapter aimed to investigate the effect of physical and mental workload combinations on auditory attentional resources, both verbal (auditory-arithmetic task) and spatial (auditory-tone localisation task). It aimed to understand the effect of different levels of physical workload on two mental auditory task loads, investigating increasing levels of physiological arousal. As stated in section 5.1, a medium level of physical exercise facilitates the tone identification reaction time task (auditory-spatial task) (Joyce et al., 2009). In addition, according to Audiffren et al. (2009), a moderate cycling workload improves the performance of participants in an auditory-verbal task (number ascending task); in addition, the authors said that the impact of physical workloads on complex auditory tasks are limited since most authors have focused on auditory reaction time tasks. Furthermore, the gender factor was considered in this study in order to understand the differences between males and females in performing auditory tasks while exercising, since according to Yagi et al (1999), gender differences while performing physical and mental tasks under different levels of interaction have received less attention. In addition, it aimed to investigate how physical workload leads to better auditory performance by supplying more oxygen to the brain and reducing brain activation due to auditory workloads.

5.5.1 Performance

The performance measurements included two dependent variables: accuracy and time of task. Generally, auditory task performance was significantly affected by physical and mental workload changes. According to Wilson and Russell (2003), the relationship between mental workload and performance is an inverted-U, as it is between physical and cognitive auditory performance (Audiffren et al., 2009). However, the results of the current chapter suggest that the medium physical level (50% Wmax) led to worse accuracy and time of task at medium auditory workloads in tone localisation or arithmetic mental tasks. Similarly, Chapter 4 showed that the medium level of physical workload led to better time of task at the medium level for visual tasks but not the best performance. Therefore, these results do not support the hypotheses of the current chapter, which assumed that the best performance in the auditory tasks would occur at medium levels of workload interactions, perhaps because the auditory tasks used in this chapter were more difficult than the visual tasks used in the experiment described in Chapter 4.

Interestingly, the results of the current study illustrated that a low physical workload (20% Wmax) led to better task time in both the arithmetic and tone localisation tasks with a medium auditory workload since there was no significant difference between times at low and medium mental workload levels. In contrast, there were significant differences between times at low and medium mental demands in both tasks under the baseline conditions (i.e., the pilot study, section 5.2.4). However, the Chapter 4 results showed that the participants had better time of task at the medium physical load versus the low and medium mental workloads. This is consistent with previous studies that found that physical activity leads to incremental increases in arousal level, which leads to better auditory cognitive performance (Yagi et al., 1999). However, in the experiments described in this chapter, the better participants' accuracy in both auditory tasks occurred at the low physical load × low mental load and medium physical load × low mental load. This is similar to the results described in Chapter 4, where the results showed that better accuracy occurred at the low and medium physical workloads × low mental workload in both visual tasks. This supports the hypothesis that a medium physical level leads to superior performance at a low mental workload in auditory tasks, so a medium level of physical load avoids any worse performance for auditory attentional resources due to the low level of arousal that occurs due to the low mental workload.

There were no significant differences between accuracy at low and medium physical loads versus a low mental workload. The results supported the hypothesis that medium physical activity led to better accuracy at the low mental auditory workload. Furthermore, there was a significant difference in accuracy between the tone localisation and arithmetic tasks at the low mental level under baseline conditions, whereas there was no significant difference in accuracy between tasks at a low physical load versus a low mental load, perhaps because the increased levels of arousal incurred by physical activity resulted in an increase in oxygenation since physical activity transfers more blood and oxygen to the brain; this could have balanced the available oxygen and the oxygen needed to complete the auditory tasks, whereas oxygenation under low mental levels is low (Perrey et al., 2010).

The results also showed that the worst accuracy and task time were observed with high interactions of physical and mental workloads; this may be because of a high level of arousal caused by high workload interaction intensity. This result supported the hypothesis of the current study, which assumed that performance in both auditory tasks would be the worst at high levels of workload combinations due to a high level of arousal. This is similar to the findings in Chapter 4, where there was worse visual task performance with overload workload interactions, perhaps because of the high level of arousal and high reduction in brain oxygen due to high mental demand. This was consistent with the results of previous studies, which have shown that high levels of physical load worsened performance on an auditory ascending number task due to high arousal (Audiffren et al., 2009).

In this chapter, there were no significant differences in accuracy between the auditory tasks. However, the arithmetic task required more time than the tone localisation task at high levels of physical and mental workload interaction. However, in the baseline condition at a high mental workload the arithmetic task also required more time than the tone localisation task. The arithmetic task needed more information processing and recall to complete it. This is not consistent with Halpern's (2000) findings, which indicated that auditory spatial tasks are usually more complex than auditory verbal tasks, since they need complex working memory actions such as recalling data from long-term memory, and they depend on imagination and orientation ability. In contrast, in Chapter 4, the results revealed no significant differences between the visual tasks in accuracy or time of tasks while cycling.

5.5.2 Physiological Parameters

The results described in Chapters 4 and 5 were similar since HR was significantly increased when the physical activity and mental visual and auditory tasks workloads increased. In the auditory experiments, the effect of physical and mental workload interactions on HR was significant and the difference between the low and medium mental workloads was less linear. For example, in the tone localisation task, there were no significant differences between HR at low and medium mental loads versus low physical demand. In contrast, there were significant differences between HR at low and medium mental levels in the baseline condition (see the pilot study) for the tone localisation task. This means that physical workload significantly increased HR, particularly at low levels of physical demand, so performance was better at the medium mental workload in both auditory tasks compared to the baseline since the physiological arousal was increased by the physical load. In addition, as stated in section 5.5.1, the medium physical workload led to better performance in both tasks at the low mental workload due to increased arousal. This was consistent with previous researchers' results, which showed that medium physical load leads to increased arousal, which then supports auditory information processing (Audiffren et al., 2008).

Similarly, the mean blood pressure (MBP) level was sensitive to physical and mental auditory workload increases. This is consistent with the results of Chapter 4, which showed significant increases in both measures and in both tasks (arithmetic and spatial figures), as visual mental and physical workloads increased. That may be because of increased stress on the cardiovascular system due to the mental auditory workload and physical exercise (Fredericks et al., 2005).

The HRV variable was sensitive to mental workload and decreased as mental auditory difficulty increased. In contrast, it increased significantly as physical loads increased. This is similar to the findings of Veltman and Gaillard (1998), who mentioned that HRV decreases significantly with more complex information processing on mental auditory tasks. In the baseline condition for the arithmetic task, lower HRV values were observed compared to the tone localisation task, which indicates that the arithmetic task was more complex than the tone localisation task. In contrast, there were no significant differences between the tasks in HRV during physical activity. That may because the physical demands led to an increase in the HRV value, so the variation in HRV decreased. This may explain why the time taken to complete the task at the low physical versus medium mental workload was better. Also, accuracy was similar at the low mental workload versus the low and medium physical workloads. The results of this chapter were similar to the findings in Chapter 4, which illustrated that HRV decreased significantly as visual mental workload increased, and it increased as physical loads increased.

5.5.3 Brain Activity

The present study found that the NIRS method was suitable to measure mental auditory loads and physical loads on attentional resources. The changes in rSO2 are sensitive to mental and physical workload fluctuations. An increase in rSO2 percentage is associated with increased auditory arithmetic and tone localisation demands. This is similar to the findings of Kashihara et al. (2009) who mentioned that increasing the level of an auditory arithmetic task led to high brain activation and errors increased. In contrast, it decreased as physical cycling loads increased. This is similar to Chapter 4's results, which showed a significant increase in rSO2 as visual arithmetic and spatial figure demands increased. The increasing rSO2 indicated that the percentage of oxygenation changes in the brain increased due an increased level of auditory mental workload, which means the amount of oxygen in the brain was not equal to the quantity necessary to meet the auditory mental workload in either mental task. In contrast, increasing the level of physical load led to a decrease in oxygenation changes by transporting more oxygen to the brain through increased blood flow. That may create a balance between oxygen available in the brain and the amount required to complete the auditory task. This would explain why mental auditory performance was better at physical load (20 and 50% Wmax) and low and medium auditory workloads interactions in the arithmetic and tone localisation tasks, as compared to the baseline condition. This result is consistent with Perry et al. (2010) who suggested that an increasing level of physical exercise affects information processing by increasing the blood flow to the brain, so the amount of oxygen delivered to the brain increases and facilitates cognitive functions. The effect of physical and mental workload interactions was significant on rSO2. However, the current results revealed no significant differences between rSO2 under medium and high physical loads at high mental workload; this may be because other parts of the body (i.e., arm and leg muscles) consume oxygen, as well as the brain, due to high physical load (Perry et al., 2010).

The present study found that the mean rSO2 percentage in the auditory arithmetic task was greater than in the tone localisation task, since participants needed more information processing resources and brain activation to complete the arithmetic task while performing the physical task (cycling). This may be because the auditory task consumed more time than the localisation task, and these results are similar to the previous physiological measures of HR, HRV and MBP. In contrast, in Chapter 4, the visual spatial figures task concurrent with cycling showed higher rSO2 percentages (i.e., higher brain oxygenation changes) than the visual arithmetic task (verbal). This could be because the figures used in the study were complex and needed high abilities of orientation and imagination, and they therefore needed more time to complete than the arithmetic task. The Pearson’s correlation test showed a moderate negative correlation between oxygenation changes and HR and MBP ($r = -0.42$, $p < 0.05$ and $r = -0.39$, $p < 0.05$), respectively which may be because the increasing level of physical workload led to rSO2 decreasing, which means an increase in brain oxygenation changes due to high mental workload decreased by physical activity. So that may reflect the better time and accuracy at the medium workload of physical and a low mental auditory workload in arithmetic and tone localisation tasks. In addition, it illustrated that the brain oxygenation variation correlated with changes in physical workload, as it did with auditory mental workloads.

5.5.4 Subjective Assessment Tools

Physical Workload Assessment Tools (Borg’s scores)

The Borg-CR10 and RPE scores were affected by the physical workloads, whereas the workloads of both auditory tasks did not impact the scores. Increasing scores in both scales were associated with physical workload increasing and indicated the sensitivity of the scale and human perceptions of changes in physical workload. These results are similar to those in Chapter 4, which indicated the significant influence on CR10 and RPE of physical cycling loads and significant differences between the physical levels. However, the scores were not sensitive to auditory arithmetic and tone localisation mental workload changes, because participants’ perceptions during the workload interactions were not affected by mental workload changes. These results are similar to findings by Fredericks et al. (2005) who concluded that the Borg scales are sensitive to physical load levels, whereas changes in cognitive word test and arithmetic task workloads did not affect them. Thus, the auditory mental activities did not influence participants’ perception of physical workload.

Numerous researchers have found that the Borg-CR10 and RPE rating scores and HR showed significant differences when perceived physical workload increased (Borg, 1987; Borg, 1988; DiDomenico and Nussbaum, 2008; Fredericks et al., 2005; Perry et al., 2008). Moreover, as expected, the Borg-CR10 and RPE scores were significantly correlated to HR, MBP, and accuracy, and this indicated that the variations in both scales' scores changed significantly as the physical load difficulty levels and physiological arousal increased. Furthermore, the Pearson correlation indicated a moderate positive correlation ($r = 0.50$, $p < 0.05$) between CR10 and RPE scores, which means that the increasing score of CR10 is associated with an increased RPE score. Also, 25% of the variation in the CR10 score can be accounted for by the variation in the RPE score. However, any removal for either score would not impact the research findings negatively. Both scales were used, however, because various individuals make physical workload judgments differently. Although some individuals evaluated physical loads based on the range of effort that occurred due to physical activity (reflected by the RPE scale), others rated physical loads depending on the range of pain that occurred throughout the physical activity (reflected by the CR10 scale; Borg, 1998; as stated in Chapter 3, section 3.3.2.4).

NASA-TLX Assessment Tool

The mental demand (MD) and physical demand (PD) dimensions in the NASA-TLX were considered in the analysis as the purpose of this research is to find the effect of physical loads on subjective assessment of mental demand as illustrated in section 5.3.3,. In terms of the mental demand subscale, the results revealed a significant sensitivity to difficulty changes between the mental auditory workload levels (low, medium and high) in both tone localisation and arithmetic tasks. The results of the current chapter were similar to the results in Chapter 4, which found a significant increase in MD score as visual mental workload increased in the arithmetic and spatial figures tasks. In contrast, the effect of physical levels on the MD score was not significant. Furthermore, the effect of physical and mental workload interactions on MD was not significant. Importantly, it can be inferred from these results that the perception of participants toward mental load while performing mental auditory activities simultaneously with physical activity was not impacted by physical activity since, the mental demand dimension score was increased while mental workload increased. The data analysis in this chapter was consistent with previous studies that found the NASA-TLX score was sensitive to changes in mental auditory demand difficulties (DiDomenico and Nussbaum, 2008; Fredericks et al., 2005). That means participants were not aware of feeling any effect on their mental perceptions activity by the physical loads so there was no impact on subjective assessment of mental demand by physical loads. In terms of PD, the results showed that the subscale was sensitive to physical workload changes, whereas it was not sensitive to mental workload changes. That means distinct physical demand change ratings were seen as an alteration in physical workloads.

In terms of the overall NASA-TLX rating, it was sensitive to increasing physical and mental auditory workloads. Astin and Nussbaum (2002) and Fredericks et al. (2005) used the NASA-TLX rating to evaluate the impact of different levels of physical activities on auditory cognitive processes, and they determined that the rating scores increased as physical and auditory mental demands increased. In addition, in Chapter 4, the TLX score increased significantly as physical and visual arithmetic and spatial figures task workloads increased. The overall TLX score increased as physical loads increased. That may be because the physical activity impacted on the TLX dimensions of performance, effort and time subscales, thus increasing the overall TLX score. Therefore, researchers should consider the physical demand dimension while using the TLX score to evaluate mental workload since most researchers assume a physical demand subscale with zero value. This could impact on the overall scale, in particular, in tasks that involve both workloads. However, the Pearson's correlation indicated that a weak positive correlation overall TLX score and accuracy and time of task (r = -0.34, $p < 0.05$ and r = 0.36, $p < 0.05$), respectively. However, the lowest scores occurred at the simple interaction condition of physical workload versus mental arithmetic tasks and spatial figures mental tasks. The results found a significant (moderate) correlation between the TLX overall workload scores and the CR10 ratings (r = 0.38, $p < 0.05$), although the correlation between TLX and RPE was a weak significance (r = 0.34, $p < 0.05$). Thus whilst there is some redundancy between the TLX and Borg's ratings for physical tasks, there are clearly still some significant elements of each of these complex subjective constructs that are not being accounted for in the other.

The results of the NASA-TLX ratings were consistent with the physiological measures. TLX scores were significantly increased as HR and MBP increased. An interesting result was that rSO2 was significantly negatively correlated with the NASA-TLX score, whereas it was not correlated with the Borg-CR10 and RPE scores.

5.5.5 Gender Differences

7. *No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level caused by physical activity and increased oxygen delivered to the brain.*
8. *At high levels of physical and mental workload combinations, men are expected to perform better than women in the auditory-spatial task, whereas women will perform better in the auditory-verbal task due to the physical workload capacity differences between genders and the high level of arousal.*

Gender Differences and Performance

In gender factor terms, the current results indicated that there were no significant differences between men and women in accuracy in the auditory tasks. However, the results showed significant differences between male and female times in auditory arithmetic tasks during a high level of physical workload while interacting with a medium or high mental load. Females spent more time than males at high physical load interactions with medium and high mental workloads in the arithmetic task. That may be because the physical activity supported and facilitated information processing at a low mental workload in both auditory tasks. The difference between genders during high physical activity may have become apparent because males have greater strength and maximum workload capacity than females (Borg, 1998). There was no gender difference in performance on the tone localisation task. This is not consistent with Zundorf et al. (2011), who found that females made a higher percentage of errors than males in audio-spatial tasks (sound localisation). In contrast, Chapter 4 found no significant differences between genders in performance in both visual tasks conditions. That may be because the arithmetic auditory task was more complex than the tone localisation task in the current chapter.

Gender Differences and Physiological Parameters

In general, females were observed to have higher mean HR and MBPs than males in the arithmetic auditory task while concurrently performing at high physical levels and medium and high mental levels. In contrast, there were no significant differences between genders in HRV. That may be because females need longer to complete auditory mental arithmetic tasks. Also, the physical workload capacity and range of strength of males are greater than for females (Borg, 1998), so the physical loads may affect females' physiological state.

There were no significant differences between genders in the tone localisation tasks. That may be because the tone localisation task was relatively simple. This is consistent with Yagi et al. (1999) who found that females had a higher HR than males while performing auditory signal reaction-time tasks at high levels of physical activity. In contrast, in Chapter 4, significant differences between males and females occurred in the visual spatial figures tasks at a high level of physical workload interacting with medium and high spatial figures mental demands, whereas there were no significant differences in the visual arithmetic task. These results were not consistent with those of Zundorf et al. (2011) who said that spatial auditory tasks normally require more information processing than verbal auditory tasks, since the spatial auditory task depends on the recognition of shapes, various locations of sounds and imagination, so it needs more time than the verbal task, which depends on words and numbers. However, the differences between the two tasks relate to the complexity of each type of task (Tomporowski, 2003).

No gender differences appeared in brain oxygenation at any level of mental and physical workload interaction in either auditory task. That may be because the relationship between physical activity and rSO2 was negative, since increasing the level of cycling resulted in less brain oxygenation changes and therefore the mean rSO2 was reduced. In contrast, rSO2 increased while mental auditory task levels increased, so the high brain oxygenation changes due to mental load were reduced by physical activity, possibly causing the gender differences to decrease. These results were consistent with Antunes et al. (2006), who mentioned that extensive oxygenation alterations in the brain due to complex mental tasks can be reduced by medium physical load, since physical movement delivers more blood and oxygen to the brain and that aids the cognitive information process.

Gender Differences and Subjective Assessment Tools

In term of Borg’s CR10 and RPE scales, females scored higher than males in both. The significant differences between genders occurred at high physical workloads and that may be because the maximum workload capacity and muscle strength are greater in men (Borg, 1998), which matches the results in Chapter 4. In addition, there was no significant difference between males and females in physical workload at low and medium levels, and that may be because the technique that was used in this experiment depended on the maximum workload capacity for each participant, which may decrease participants’ feelings of perceived physical loads at different levels from one participant to another.

In term of the NASA-TLX score, there were no significant differences between genders in MD rating scores in either auditory task, and also there were no significant differences in overall TLX score. These results were similar to findings in Chapter 4, in that the female and male overall TLX score under all workload interactions were the same in both visual tasks.

5.6 CONCLUSION

This chapter aimed to investigate the impact of physical and mental workload combinations on auditory resources, investigating both an auditory-verbal resource (auditory arithmetic task) and an auditory-spatial resource (tone localisation task). The concurrent physical and mental workloads influenced individuals’ performance. Generally, the results confirmed that a low physical load (20% Wmax) led to significantly better time of task in both auditory tasks, particularly at medium mental workloads. In addition, the participants performed better in accuracy at the low and medium physical workloads (20% Wmax and 50% Wmax) versus the low mental workload in both auditory tasks. However, the medium physical workload did not lead to the best performance at the medium level of mental workload in either task. The low physical workload, compared to the baseline condition, led to better auditory task performance at the medium mental workload by increasing the level of physiological arousal and reducing the brain oxygenation by decreasing the rSO2. The physiological variables increased significantly as the mental workload and physical activity increased. Performance worsened significantly with the overload of physical and mental workload combinations in both auditory tasks. However, a high level of physical load (80% Wmax) led to the worst time taken to complete the auditory arithmetic task at the high mental load, as well as the worst accuracy. That may be because the auditory arithmetic task used in this experiment was more complex than the tone localisation task.

The auditory arithmetic task carried out simultaneously with the physical task was more difficult than the tone localisation task, indicated by the fact that the participants spent more time completing the arithmetic task than the tone localisation task at a high level of physical workload versus the medium and high mental workloads. In contrast, there was no significant difference in accuracy between the auditory tasks.

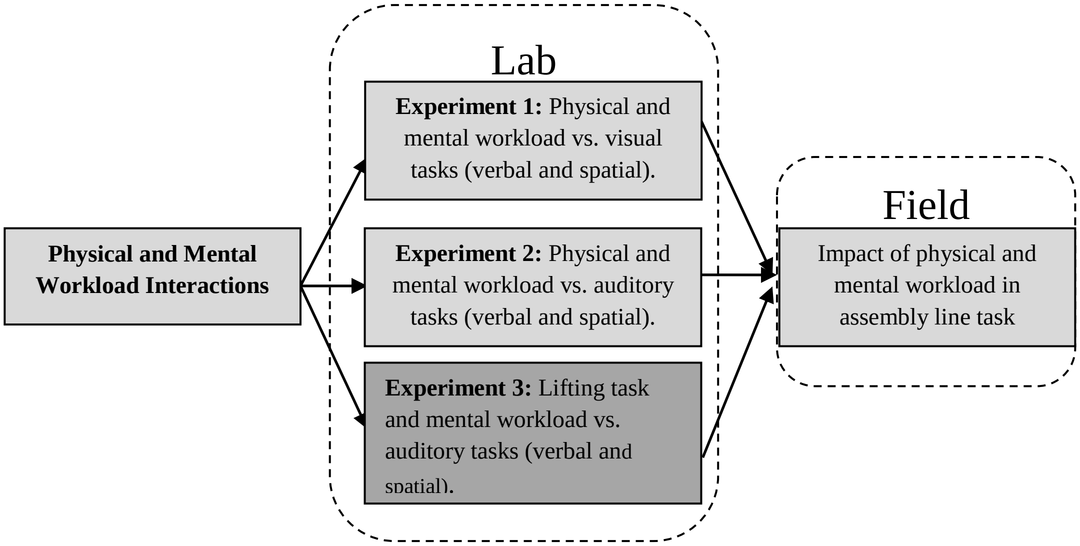
In terms of gender differences, there was no significant difference between genders in accuracy in either auditory task. Females spent more time than males in arithmetic auditory tasks at a high physical demand versus medium and high mental loads. In addition, significant differences between genders appeared in the arithmetic task at high levels of workload interaction, as was reflected by HR and MBP physiological measures. There were no gender differences in the tone localisation task condition.

The more interesting result was that increasing levels of physical workload led to a decrease in the oxygenation changes in the brain due to increased levels of auditory workload. The rSO2 decreased while physical workloads increased, and rSO2 increased as the mental auditory workload increased.The important suggestion is that, since the impact of physical workload on the mental demand dimension was not significant, the individual does not perceive the impact of physical workload on their mental auditory workload, since the physical workload level alterations did not influence participants' mental workload perception the impact of mental workload on the physical subscale was also not significant. However, the subjective assessment of the NASA-TLX overall score was sensitive to physical and mental demand changes. However, according to the overall TLX score, the TLX increased significantly as the physical and mental workloads increased, so it indicates that the TLX is a valuable subjective measure of multitasking demand workloads. The Borg-CR10 and RPE were affected by physical load difficulty but were not affected by the level of the tone localisation or arithmetic mental task.

Thus, in this chapter, it was shown that the low and medium physical workloads led to better performance (i.e., accuracy and time of task) at a low auditory mental workload for both auditory resources in Wicken's model (1984), which are auditory-verbal and auditory-spatial resources, through increasing the level of physiological arousal and transferring more oxygen to the brain, similar to the results described in Chapter 4, which explained the benefits of low and medium physical workloads during the visual task performance. Therefore, another experiment (described in Chapter 6) was conducted to understand the contribution of the interaction of a physical lifting task, instead of a cycling task, with mental workload on auditory tasks. This physical task was selected since a lifting task is more applicable to the real-world domain. In addition, as mentioned in section 3.1, this thesis includes a field study implemented in an assembly line, and the lifting task was chosen to simulate this type of job. However, because it is difficult to set up visual tasks while lifting, auditory tasks were used in the experiment described in Chapter 6.

CHAPTER 6 -Experiment 3:

INFLUENCE OF PHYSICAL LIFTING TASK AND MENTAL WORKLOAD INTERACTIONS ON AUDITORY ATTENTIONAL RESOURCE PERFORMANCE



6.1 INTRODUCTION AND EXPERIMENTAL HYPOTHESES

This chapter investigates the impact of physical lifting and mental workload combinations on auditory tasks (verbal and spatial) as stated in Chapter 3 (see Table 3.2). The physical task was lifting boxes, since this is more applicable to real life than the cycling task. In addition, this physical task was used to simulate a subsequent field study implemented in a product assembly line. Auditory tasks were selected as it is difficult to set up visual tasks to perform concurrently with lifting boxes. In fact, a lifting task has not often been used by previous researchers; however, two studies used this type of task and demonstrated that different physical levels of lifting boxes (8%, 14%, and 20% of body mass) did not have any impact on a simple auditory arithmetic task (DiDomenico and Nussbaum, 2008, 2011). However, they did not consider the effect of workload interactions on attentional resources along two of Wickens' (2008) dimensions: input modality (visual vs. auditory), and processing code (verbal vs. spatial). In Chapter 4 the impact of physical and mental workload interactions on visual tasks (arithmetic and spatial figures tasks) was studied. In contrast, Chapter 5 tested the effect of physical and mental workload combinations on auditory tasks (arithmetic and tone localisation tasks). It is worth noting, as mentioned in Chapter 2, that some researchers have found that a medium-level cycling exercise improved an auditory-verbal task (tone sound reaction time task) (Joyce et al., 2009) Moreover, moderate physical exercise improved performance in a verbal-auditory task (ascending number task) (Audiffren et al., 2009). In addition, they reported that the correlation between physical load and auditory performance was an inverted-U, since an increased physical load led to increased arousal. Furthermore, the correlation between mental workload and auditory performance is a curved line because arousal level decreases under overly simple mental tasks (Wilson and Russell, 2003). The hypotheses presented below were derived from the main hypothesis of the thesis (see section 2.8) and were not dependent on the results of the experiments in Chapter 5, since each main experiment was based on the main hypotheses that were derived from the literature review. As a result, the hypothesis derived from this review is as follows:

- *The participants' best performance will occur at medium physical lifting × medium mental auditory workload interactions.*
- *The participants' worst performance will occur with a high physical lifting and high auditory mental workload interactions due to the high level of arousal.*
- *Participants will perform better at medium physical lifting × low auditory mental (verbal and spatial) workload interactions due to an increased level of arousal by physical workload.*
- *Participants' performance will be worse with low physical lifting workload × low auditory mental workload interactions due to a low level of arousal.*

According to Perrey et al. (2010), increasing brain oxygenation is associated with increased auditory mental workloads. Since a high level of auditory demand reduces the amount of oxygen in the brain, performance will suffer. However, some researchers have stated that relatively high levels of physical workload transport more oxygen and blood to the brain, which supports and improves auditory information processing and attentional verbal and spatial resources (Antunes et al., 2006). As yet, no previous study has examined the effect of lifting task loads on brain activity during auditory task performance. Therefore, in the current experiment in term of oxygenation changes, the hypothesis for this experiment is as follows:

- *The participants' best performance will occur with medium physical lifting× low auditory mental workload. The participants will perform better with medium physical lifting × medium auditory mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of the physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.*
- *The participants' worst performance will occur with high physical lifting and high auditory mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high auditory workload since the increasing level of auditory mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the auditory workload.*

According to Spierer et al. (2010), men outperform women in auditory-spatial tasks, whereas women excel in auditory-verbal tasks. However, the differences between genders in auditory tasks depend upon the complexity of the tasks. In addition, some levels of physical activity undertaken simultaneously with mental auditory tasks could reduce gender differences in performance. For example, Yagi et al. (1999) found that men were better than women in an auditory-tone reaction time task, but no significant difference occurred at a low level of physical load, whereas a difference appeared at a high level of physical activity, since women's reaction time was higher than that of men. In addition, women have a higher mean heart rate than men. Thus, the hypothesis derived from this review is as follows:

- *No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level by physical activity and increased oxygen delivered to the brain.*

- *At high levels of physical and mental workload combinations, men are expected to perform better than women in the auditory-spatial task, whereas women will perform better in the auditory-verbal task due to the physical workload capacity differences between genders and the high level of arousal.*

6.2 STEP ONE -PILOT STUDY

This pilot study was conducted to verify and validate the three levels of difficulty in the lifting task that was used in this experiment as a physical task instead of the cycling task. It is important to examine the three difficulty levels of physical lifting workload and verify them as low, medium and high workloads. Therefore, the aim of this study was to test and validate these levels. The levels were: low physical workload, lifting and putting down boxes with 8% of body mass; medium physical workload, lifting and putting down boxes with 14% of body mass and finally, the heavy load was 20% of body mass. These percentages were used previously by DiDomenico and Nussbaum, (2008, 2011).

6.2.1 Experimental Design

The experiment contained one independent variable which was the physical workload level (low, medium and high, as described above). In addition, it included physiological parameters, heart rate and blood pressure, and subjective assessment tools including the Borg-CR10 and RPE scales.

Physical Task

The box lifting task was used to create the physical demand. This protocol included three different load weights (low, medium and high) in order to produce different levels of physical load difficulty. These workloads are (8%, 14% and 20% of body mass, as mentioned previously). However, the percentage of body mass was used of instead of 1-rep maximum method since; all participants were fit and healthy, with no problem or medical operation in the back, arms and shoulder, and having a frequent exercise routines at least once per month. In addition, the participants were not have any musculoskeletal injuries within the previous 12 months and they were completed the health questionnaire (see Appendix B). Following Garg and Saxena (1980), a percentage of 1-rep maximum method was used to determine the maximum acceptable weight of lift. However, the 20% body mass in the current experiment is not considered the maximum acceptable weight. It was the high physical workload and the participants were familiarised with this workload. They confirmed this percentage as a high physical workload lifting load but not as the maximum acceptable weight of lift. Therefore, this workload was difficult but not too heavy.. According to Lindbeck and Kjelberg (2001), the percentage of mass method reduces the differences between both genders in physical capacity, particularly if all participants are healthy. However, Lindbeck and Kjelberg (2001) used the lifting mass load of the body (kg) to determine the difference between males and females in physical lifting performance.

The box to be lifted had the following dimensions: 0.35×0.35×0.30 m, where 0.30 m was the distance between cut-out handles. There were two cut-out handles 0.25 m above the bottom, with dimensions 0.20×0.08 m (see Figure 6.1). These box dimensions were selected to be identical to the standard lifting box size guidelines (Mirka et al., 1994). The mass of the box was 4 kg; this is the maximum mass recommended in order to reduce any risk or fatigue through lifting and putting down the box. Also, these dimensions reduce the impact of box size on gender differences (Mirka et al., 1994). This variable contained three levels: low effort (low percentage of body mass), medium (medium percentage body mass), and high effort (high portion of body mass). This variable was the same in both experiments.

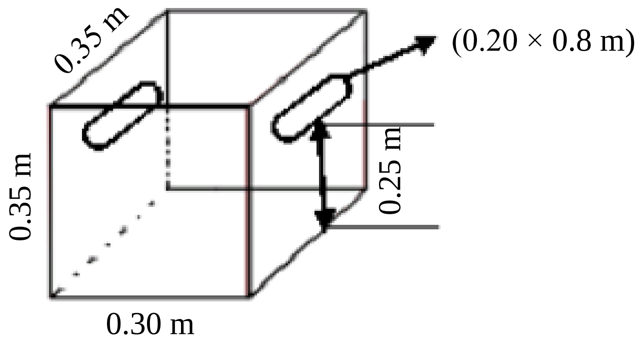


Figure 6.1 Schematic diagram of the box dimensions used in the experiment

6.2.2 Participants

Twelve healthy participants between the ages of 25 –35 years old, six male and six female, participated in this experiment. All were recruited from Brunel University. The descriptive statistics for the participants are given in Table 6.1. No participant reported any back or musculoskeletal problems within the past 12 months and they all completed a health questionnaire (see Appendix B). The study was approved by the Brunel University Ethics Committee (see Appendix E)

Table 6.1 Descriptive statistics for participant sample

	Male(n=6)		Female (n=6)	
Variable	Mean	SD	Mean	SD
Age (year)	28.2	2.16	29.3	3.53
Height (cm)	175.91	4.52	162.33	5.26
Weight (kg)	86.03	6.31	63.2	6.02

6.2.3 Procedure

The participants were provided with an introduction to the experiments, outlining the steps involved. They were then asked to fix the heart rate monitor and blood pressure recorder (Finometer) so that HR and MBP could be measured continuously. Then they were asked to lift the first box (A), using its handles, from the floor onto a table 0.69 m high, and take the second box (B) from the table to a signed target on the floor, as illustrated in Figure 6.2. The frequency was 4 lifts/min since, according to Karwowski (1998), this number of lifts is the most efficient to elucidate the effect of physical lifting. Each subject was required to complete three conditions and the allotted time for each condition was five minutes. The selection of condition was randomised. After each condition the participant took around five minutes rest until their HR reached resting level. During these rest periods they completed the Borg-CR10 and RPE ratings (see Appendix H).

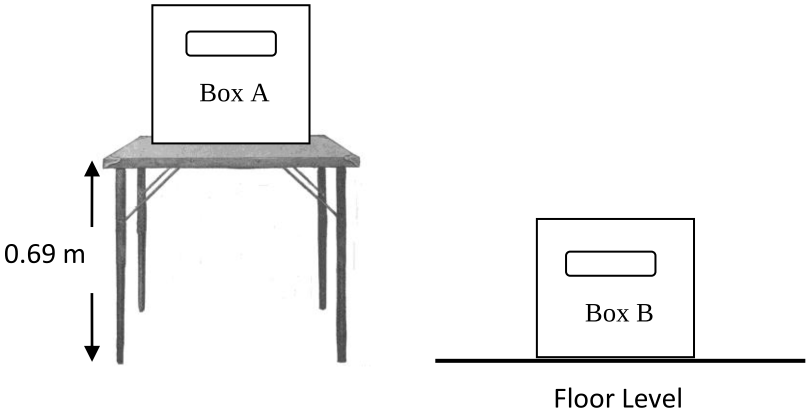


Figure 6.2 Front views of both boxes and the table height level

6.2.4 Results and Conclusion

6.2.4.1 Physiological Parameters

Mauchly’s test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for both parameters HR and MBP ($p<0.05$), so the F-adjusted was used. The ANOVA analysis was used to find the impact of physical workloads on physiological parameters. Heart rate and mean blood pressure were measured to reflect the increasing workloads of the lifting task. The ANOVA analysis showed that heart rate was significantly affected by the changes in the box lifting task workloads ($F(1.3,14.3) = 45.36$, $p<0.01$). Furthermore, the increasing workloads of lifting weights led to an increase in participants’ HRs (Figure 6.3). Contrast analysis showed a significant difference in HR between low physical workload vs. medium workload ($p<0.01$) and between medium workload vs. high workload ($p<0.01$). The analysis illustrated that changes in the mass of boxes significantly influenced mean blood pressure ($F(1.6,17.2) = 67.99$, $p<0.01$). The highest magnitude of MBP appeared at the high lifting load compared with low workload (Figure 6.4). Also, contrast analysis showed that there was a significant difference between blood pressure at a low workload vs. medium workload ($p<0.01$) and medium workload vs. high workload ($p<0.01$).

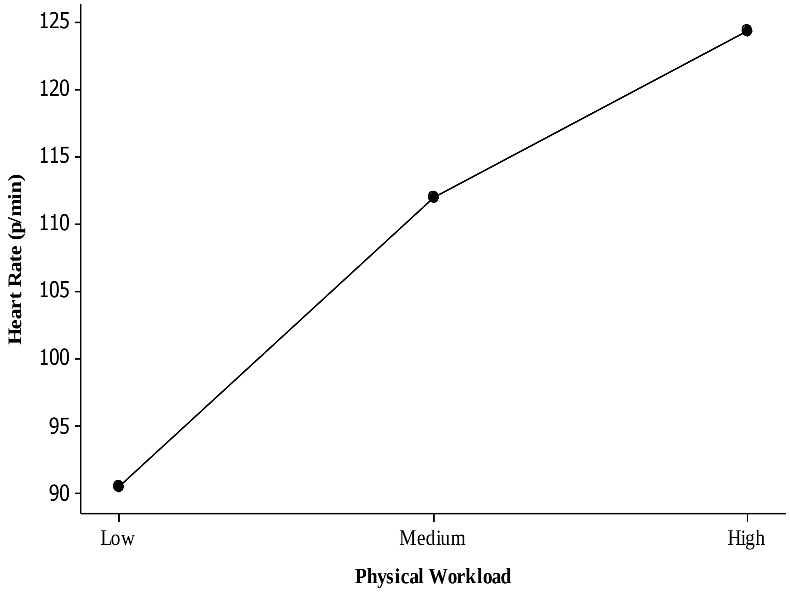


Figure 6.3 Mean heart rate implies correlation three workloads of lifting task

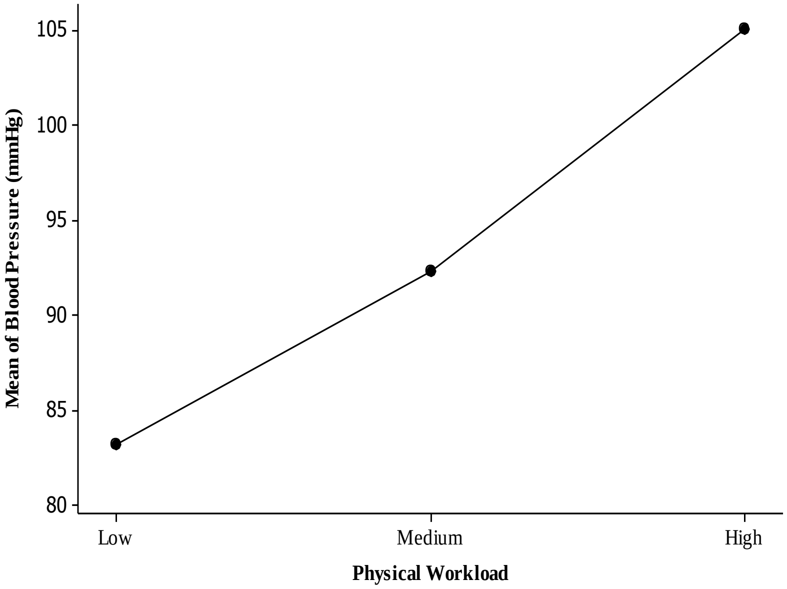


Figure 6.4 Mean blood pressure implies correlation three workloads of lifting task

6.2.4.2 Subjective Assessment Tools

Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for both parameters Borg's scales (CR10 and RPE) (p<0.05), so the F-adjusted was used.

Borg-CR10 and Borg-RPE scales were used to evaluate the three workloads of lifting task in order to identify whether the three levels were perceived to be distinct. The analysis showed that increasing workloads of box mass were associated with increased scores in both Borg scales. The physical lifting task workloads significantly impacted on the CR10 and RPE scores ratings, ($F(1.8,19.9) = 543.02$, $p<0.01$) and ($F(1.5,16.7) = 373.94$, $p<0.01$, respectively), as shown in Figure 6.5 and Figure 6.6. According to the contrast analysis there were significant differences in CR10 between low physical workload vs. medium workload ($p<0.05$) and between medium workload vs. high workload ($p<0.05$). In addition, there were significant differences in RPE between all three physical workloads ($p<0.05$).

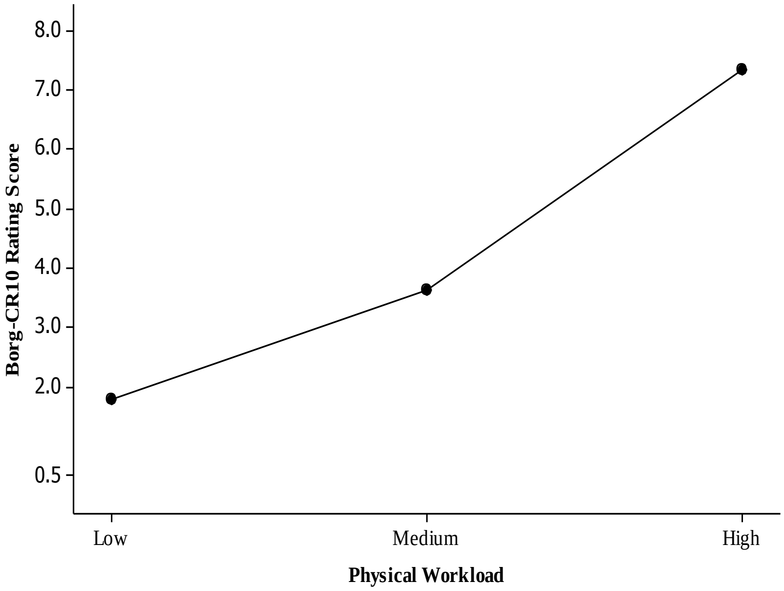


Figure 6.5 Mean of Borg-CR10 against three workloads of lifting task

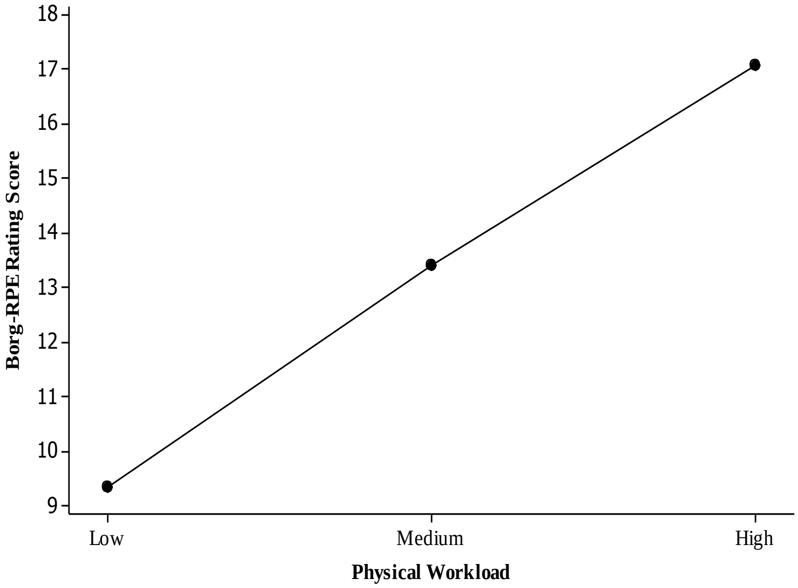


Figure 6.6 Mean of Borg-RPE against three workloads of lifting task

In conclusion, the three difficulty workloads of lifting task (physical workload) were satisfied and validated, since mean heart rate and blood pressure were sensitive to the change in box mass. Furthermore, there was a significant difference in HR between low physical workload vs. medium and medium workload vs. high physical lifting load. The blood pressure findings also showed a significant difference between the three lifting workloads. In addition, the scores of both Borg CR10 and RPE increased significantly when the lifting task increased, indicating that perceived physical load matched the objective metrics. This is similar to the results of DiDomenico and Nussbaum (2008) who concluded there were significant differences between these box lifting load workloads. Furthermore, the contrast analysis showed a significant difference in both scales and physiological measures when lifting workload changed from low to medium and from medium to high workload. Therefore, these three workloads of physical lifting tasks were verified as distinct.

6.3 MAIN STUDY METHOD

6.3.1 Experimental Design

The design was similar to that in Chapter 5, although a lifting task had been substituted for the cycling task. The current study involves one experiment to examine the impact of the interaction of physical lifting workload and mental workload, under three different conditions, and to examine the effect of physiological arousal on operator attentional auditory resources. Two auditory mental tasks were used: -verbal (arithmetic) and spatial (tone localisation), as illustrated in Table 6.2. The hypotheses presented in Table 6.2 were derived from the main hypothesis of the thesis (see section 2.8) and not dependent on the results of previous chapters, since each main experiment was derived from the main hypotheses, which in turn were derived from literature review. Repeated measure analysis was used for the *within-subjects factor* (three physical and mental workload levels of interactions) and for the *between-subjects factor* (types of auditory mental tasks (i.e., verbal and spatial tasks)) and genders.

Table 6.2 The nine conditions of interaction between physical load and mental auditory arithmetic and tone localisation tasks

		Mental Auditory Arithmetic Workload OR Tone Localisation Workload (MWL)		
		Low mental load	Medium mental load	High mental load
Physical Workload (PWL)	Low lifting load (8% body weight)	Participants' performance will be worse	Participants' performance will be worse	Participants' performance will be worse
	Medium lifting load (14% body weight)	Participants' performance will be better	Best performance will occur under this condition	Participants' performance will be worse
	High lifting load (20% body weight)	Participants' performance will be worse	Participants' performance will be worse	Worst performance will occur under this condition

6.3.2 Experimental Tasks

- ***Mental Auditory Arithmetic Task (verbal task)***

To avoid the repetition the arithmetic task was presented aurally and included three levels of difficulty similar to those presented in Chapter 4 (see section 4.2.1).

- ***Mental Tone Localisation Task (spatial task)***

In this task the participants needed to determine the source of a pure tone (by identifying the speaker generating the pure tone). This task was the same as the tone localisation task in the previous chapter and all details regarding the three difficulty levels of this task and its validation were explained in the pilot study in the previous chapter (section 5.2.1).

- ***Physical Task***

A box lifting task was used to simulate the physical workloads with three different level of difficulty workload (low, medium and high):

- **Low level:** 8% of body mass
- **Medium level:** 14% of body mass
- **High level:** 20% of body mass

The details of this task and box specification and validation of difficulty workloads were described in section 6.2.1.

6.3.3 Outcome Measures

As mentioned in Chapter 3 (section 3.2.2), all outcome measures (i.e. dependent variables) were similar across all experimental studies. There were four main outcome measures: Performance (accuracy and time of task), physiological measures (HR, HRV and MBP), rSO2 (oxygenation changes in the brain, physiological measure) and subjective assessment tools (NASA-TLX, Borg-CR10 and Borg-RPE). In addition, the mental demand dimension (MD) and physical demand dimension (PD) were analysed using NASA-TLX analyses as illustrated in Chapter 3 (see section 3.3.2).

6.3.4 Participants

Two groups of 15 participants, females and males aged 25–35, participated in the experiment. The first 15 participants took part in the first experiment, physical lifting workload vs. auditory-verbal mental task. The other 15 participants were recruited for the second experiment, physical lifting workload vs. auditory-spatial mental task. The statistical descriptions of male and female participant groups across the experiment are illustrated in Table 6.3. The descriptive statistics of the participants' physiological measures are given in Table 6.4. The study was approved by the Brunel University Ethics Committee (see Appendix E).

Table 6.3 Statistical explanation of participants' in the experiment

Total participants	Physical workload vs. verbal mental task(Gender)	Physical workload vs. spatial mental task (Gender)	Age range	Male (Mean ± SD)	Female (Mean ± SD)
30	15 (M=8,F=7)	15 (M=8,F=7)	25–35	(31.4± 4.2)	(28.1 ± 3.6)

Table 6.4 Statistical summary and mean and standard deviation of participants' and their physiological variables at rest period for auditory arithmetic and tone localisation

	Arithmetic(n=15)	**Tone Localisation(n=15)**
Variable	*Mean± SD*	*Mean± SD*
Age (years)	30.35± 5.02	28.12 ± 4.33
Height (cm)	179.0± 7.05	167.8 ± 6.72
Weight (kg)	84.13± 8.75	65.17± 7.20
HR at rest level (bpm)	78.54 ± 10.12	81.42 ± 8.21
MBP at rest (mmHg)	81.73 ± 9.54	77.33 ± 7.33
rSO2 at rest level (%)	59.02 ± 5.79	56.35± 8.93

6.3.5 Materials and Equipment

As stated in Chapter 3 in section 3.2.3, most equipment and materials were similar across all experiments, the details of which were presented in Chapter 3 (section 3.2.3), except for the boxes which are described in section 6.2.1.

6.3.6 Procedure

Box Lifting Task vs. Auditory Arithmetic Task

At the beginning, the participants were given a short introduction about the experiment in order to familiarise them with the steps. All participants completed a health questionnaire (see Appendix B) and they submitted a participant information sheet (see Appendix E) and informed consent (see Appendix F) before the start of the experiment. Similarly to the previous experiments, they were then asked to affix all physiological equipment and the NIRS. The experiment was completed in one visit. The experiment included nine conditions and counterbalancing between conditions was carried out in order to reduce potential carryover effects and fatigue.

The experiment was started and the participants were required to lift and put down the boxes between the floor and a 0.69 m-high table. They needed to do 4 lifts/min and, as there are two safe lifting methods, squat or stoop, they were free to select their choice of body posture while lifting the boxes. The participants were informed that the squat posture was safer (Lindbeck and Kjellberg, 2001), but they were instructed to use whichever technique they found more comfortable. Both boxes were supported with two handles and the box dimensions were as mentioned in section 6.2.2. The table was placed in front of the participant and the target for the boxes was visible on the floor in front of them. The subject was asked to lift and put down, and to keep facing the front. The subject was asked to lift one box from the floor to the table and a second one from the table to the target on the floor. Simultaneously, they were asked to solve arithmetic problems for the arithmetic task which comprised two digit numbers that were presented verbally (i.e., 34 + 56 =?). The specification details of the sound which was generated from the speaker was mentioned in the previous chapter (see Chapter 5, section 5.2.3).

Each participant completed all nine conditions. Also, each participant completed 25 questions within each level as accurately and quickly as possible in the allotted six minutes. They were instructed to answer the problem verbally while carrying out the lifting task and the answer was entered by the experimenter within an allotted fixed time of five seconds, to ensure that data entry did not impact the participant's answer speed. The number of correct responses and the actual time required to complete the section was recorded directly by the software. After each trial, the participant rested for five minutes until their heart rate reached resting level. Also, immediately after completing each trial, participants were asked to complete the NASA-TLX scale (see Appendix F) and the Borg CR10 and RPE scales (see Appendix G) during the rest period between each level.

Box Lifting vs. Tone Localisation Task

In the second experiment (i.e., tone localisation task), participants used identical measures and equipment to those in the previous experiment. At the beginning, the participant was centered in the experiment room (details of the room and sound specification are given in section 3.2.3). In addition, the boxes and table were located in the front of the subject and they were asked to lift the boxes as described in the previous experiment. They were asked to keep their faces to the front as head movement can affect tone identification. (The details of sounds, speaker organisation and levels are given in the previous chapter in section 5.2.1). The speakers were placed in the room in different positions and were assigned a number as mentioned in Chapter 5 (see section 5.2.3). The speaker placed at 270^o from the participant was assigned number 1; at 30^o, number 2; at 60^o, 3; at 90^o, 4; at 120^o, 5; and at 150^o, 6. Speaker number 1 was fixed across all levels so, at the low level they were asked to select between two speakers (1 and 2), which produced two tones (pure tone and white noise) concurrently and participants were asked to select speaker that produced the pure tone. At the medium level they were asked to determine the pure tone from any two of speakers 1, 2, 3 and 4 which produced the pure tone and white noise concurrently. At the high level of the tone localisation task they were asked to identify the pure tone while all six speakers were activated. Participants identified the relevant speaker verbally concurrently with the lifting task and the answer was entered by the experimenter within the allotted fixed time of five seconds to reduce any influence by the experimenter on the participant's apparent answer speed. Each condition level included 25 problems, and participants were given six minutes to complete each level. In addition, they took five minutes to rest and complete the NASA-TLX score and Borg's CR10 and RPE scales between each condition.

6.4 RESULTS

The descriptive statistics (mean ± standard deviation) for all measures (accuracy, time of task, HR, HRV, MBP, rSO2, Borg-CR10, Borg-RPE and NASA-TLX scores) across all nine physical and mental workload interaction conditions are illustrated in Appendix I.

6.4.1. Performance

Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for both parameters accuracy and time of task measures ($p<0.05$), so the F-adjusted was used.

Accuracy

The ANOVA outputs showed that the effects of the physical lifting workloads were significant ($F(1.9,49.3) = 107.34$, $p<0.01$). In addition, the accuracy variable was impacted significantly by mental workload level changes ($F(1.9,51.7) = 94.03$, $p<0.01$). The effects of physical lifting × mental workload interaction was significant on accuracy value ($F(3.6,94.6) = 18.83$, $p<0.05$). Generally, increasing levels of physical × mental workload interaction in both tasks (arithmetic and tone localisation) led to worse accuracy (Figure 6.7.)

The differences between the levels of physical and mental workloads are now presented. According to the contrast analysis, there was a significant difference between the low workload vs. medium workload and medium workload vs. high workload ($p<0.01$ and $p<0.01$, respectively) physical lifting workload in both tasks, except there were no significant differences between low and medium physical lifting loads at low mental demand in both arithmetic and tone localisation tasks ($p=0.92$ and $p=086$, respectively) in both tasks. Additionally, the analysis showed a significant difference between mental workload levels, low workload vs. medium workload and medium workload vs. high workload in both tasks (*p*<0.01 and *p*<0.01, respectively). The impact of task type factor was not significant (*F*(1,26) = 2.97, *p*=0.128).

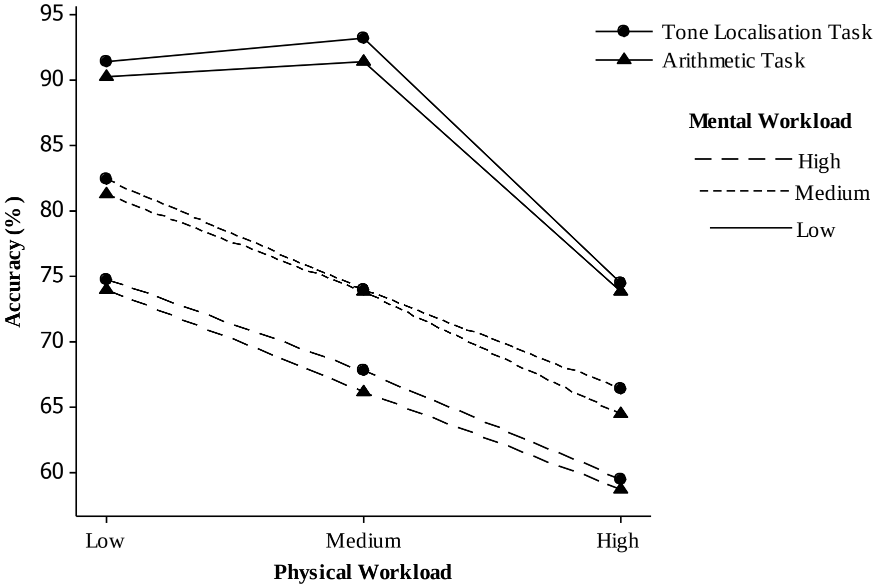


Figure 6.7 Mean accuracy percentage for tone localisation and mental arithmetic auditory tasks responses against physical lifting and mental workload interaction

Time of Task (Cumulative Time of Task)

The ANOVA technique showed that mental workload significantly impacted on participants' time (*F*(1.9,49.6) = 4153.25, *p*<0.01). In addition, the physical workload factor also significantly impacted on participants' time of task (*F*(2,52) = 798.51, *p*<0.01). Moreover, the effects of physical and mental workload interactions on time of task were significant (*F*(3.3,84.5) = 88.39, *p*<0.01), as shown in Figure 6.8.

The contrast analysis illustrated that there was a significant difference between the lifting workloads in both tasks, low workload vs. medium workload and medium workload vs. high workload (*p*<0.01 for both), except between low and medium physical lifting at low mental workload in both arithmetic and tone localisation tasks (*p*=0.074 and *p*=0.067, respectively). However, the analysis revealed a significant difference between mental workload levels, low workload vs. medium workload and medium workload vs. high workload (*p*<0.01 for both). In contrast, there were no significant differences between times at low and medium mental demands with low lifting physical load (8% of body mass) in the arithmetic and tone localisation tasks (p=0. 42 and p=0. 39, respectively).

However, the impact of task type factor was significant on time of task ($F(1,26) = 10.92$, $p<0.05$). According to Tukey's test, the difference between tasks appeared at medium and high physical lifting load × high mental workload ($p<0.05$ for both) and high physical load × medium mental workload ($p<0.05$). In contrast, there were no significant differences between tasks under other workload interactions ($p>0.05$).

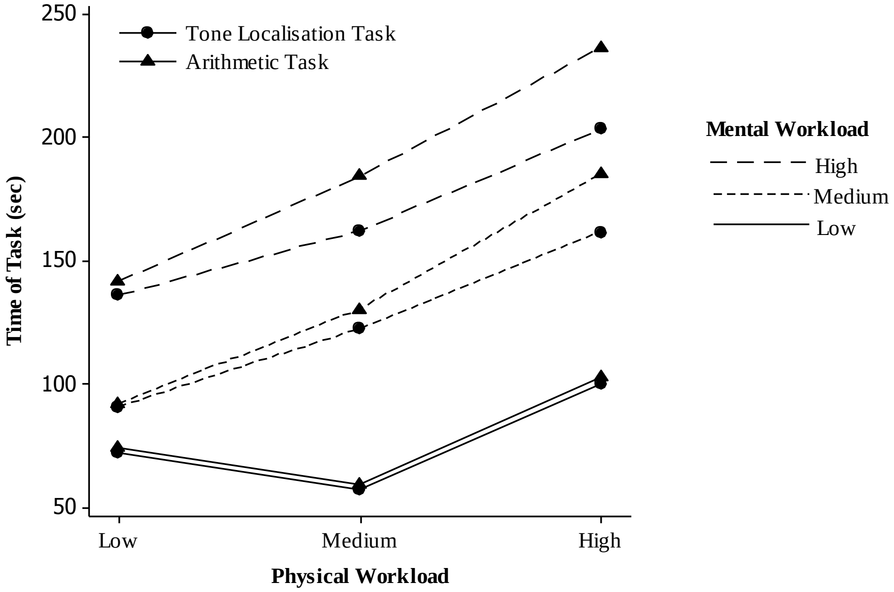


Figure 6.8 Mean of task time of both auditory tasks against workload interactions

Gender Differences and Performance (Accuracy and Time of Task)

The results showed that the effects of gender on accuracy were not significant ($F(1,26) = 2.90$, p=0.21). The influence of the gender factor was significant on time of task ($F(1,26) = 12.62$, $p<0.05$). Tukey's test showed that there was no significant difference between males and females in either task's interactions with physical workload ($p>0.05$), except in the arithmetic task at high lifting physical loads vs. medium mental load ($p<0.05$) and high lifting physical workload vs. high mental workload ($p<0.05$) (See Figure 6.9).

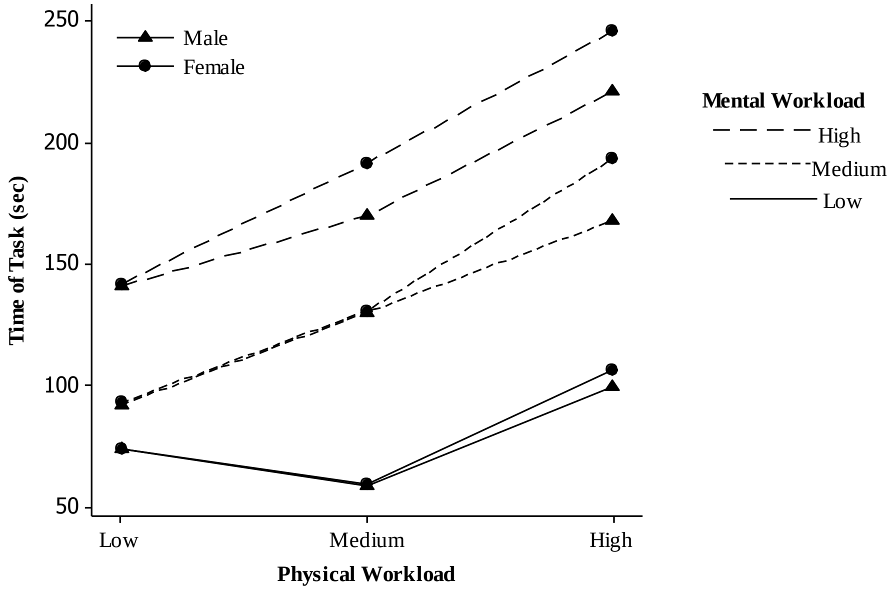


Figure 6.9 Mean time of task for males and females in the auditory arithmetic task during physical and mental workload interaction

6.4.2 Physiological Parameters

Mauchly's test was used to check the assumption of sphericity. However, the test showed that the assumption of sphericity was not met for HR, HRV and MBP and rSO2 ($p<0.05$), so the F-adjusted was used.

Heart Rate (HR)

There was a significant impact of mental workload on participants' HR ($F(1.7,43.4) = 1210.02$, $p<0.01$) in both tasks. Furthermore, lifting workload levels in both auditory tasks (arithmetic and tone localisation) significantly affected participants' HR ($F(1.3,33.3) = 3120.51$, $p<0.01$). In addition, the physical lifting and mental workload interactions significantly influenced HR ($F(2.5,65.4) = 10.85$, $p<0.05$). Generally, mean HR significantly increased as physical and mental workload increased (Figure 6.10). Tukey's HSD analysis indicated that at high levels of mental workload versus high physical loads, the arithmetic task generated a higher HR ($p<0.05$).The repeated contrast test showed a significant difference between mental workload levels ($p<0.01$) for low vs. medium level and medium vs. high level. Also, significant differences were found between HR in physical workload under all levels of interaction ($p<0.05$ and $p<0.05$), except in the tone localisation task where there was no significant difference between low and medium mental workloads at low physical lifting level (p=0.074). The impact of task type was not significant ($F(1,26) = 0.377$, $p=0.50$).

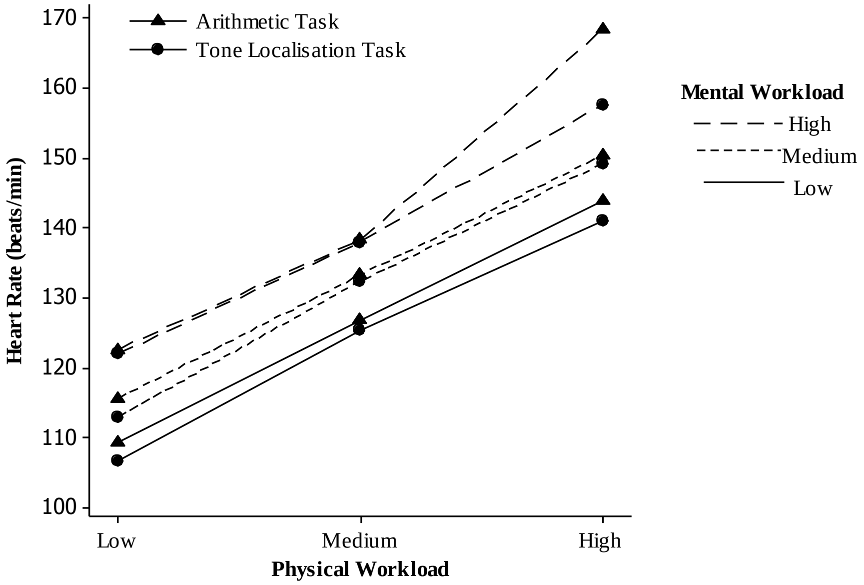


Figure 6.10 Mean heart rates during tone localisation and mental arithmetic auditory tasks against box lifting interaction

Heart Rate Variability (HRV)

Mental workload had a significant impact on participants' HRV ($F(1.5,37.9) = 250.35$, $p<0.01$). Furthermore, lifting workloads significantly impacted on participants' HRV ($F(1.6,42.5) = 159.09$, $p<0.01$). Heart rate variability significantly increased as physical lifting loads increased, whereas it decreased while mental auditory loads increased (Figure 6.11). Moreover, the physical and mental workload interaction was a significant influence on HRV ($F(3.1,79.5) = 18.89$, $p<0.05$).

The repeated contrast analysis revealed a significant difference between HRV in the lifting workload ($p<0.05$) for low lifting level vs. medium level and medium vs. high level, except between medium and high physical lifting levels in the arithmetic task at medium and high mental workloads there was no significant differences ($p=0.44$ and $p=0.39$, respectively). In addition, there were significant differences between HRV in mental workload levels for low vs. medium level and medium vs. high level, ($p<0.01$ for both).

The impact of task type on HRV was significant (*F*(1,26) = 16.34, *p*<0.05). The auditory arithmetic task run concurrently with physical workload showed a lower HRV mean than the tone localisation task. However, Tukey's test revealed significant differences in HRV between both auditory tasks during high physical level × medium mental workload (*p*<0.05) and during high physical level × high mental workload (*p*<0.05). However, there were no significant differences between the tasks under other conditions of physical and mental workload interactions (*p*>0.05).

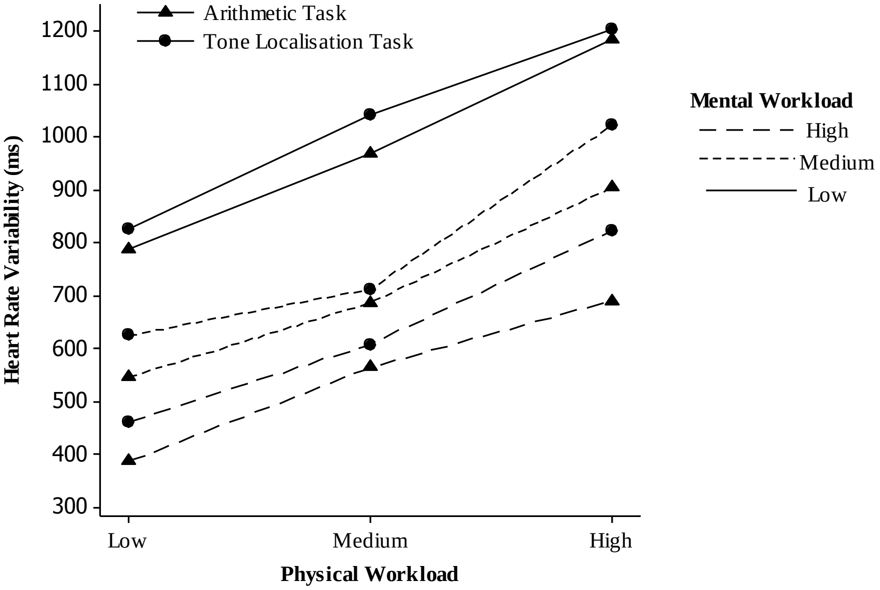


Figure 6.11 Heart Rate Variability against the lifting task interactions with mental arithmetic and tone localisation tasks

Mean Blood Pressure (MBP)

The analysis showed that mental workload significantly impacted the participants' mean blood pressure (*F*(1.9,48.6) = 298.52, *p*<0.01). In addition, the physical workload had a significant impact on participants' mean blood pressure in both tasks (*F*(1.9,48.6) = 655.11, *p*<0.01). Moreover, the effects of physical and mental workload interactions on MBP were significant (*F*(3.1,80.3) = 6.12., *p*<0.05). In addition, as both the mental task levels increased, average mean blood pressure increased (Figure 6.12). Tukey's HSD analysis indicated that at high levels of mental workload versus high physical loads, the arithmetic task showed a higher MBP (*p*<0.05).

The repeated contrast test showed a significant difference between mental workload levels for low vs. medium workload and medium vs. high workload (*p*<0.01 for both). Also, significant differences between MBP in physical workload for low physical level vs. medium level and medium vs. high level were observed (*p*<0.01 for both). However, in the tone localisation task there was no significant difference between low and medium mental workloads at low physical lifting workload (*p*=0.082). The variance analysis showed that effects of type of task on MBP were not significant (F(1,26) = 0.704, *p*=0.391).

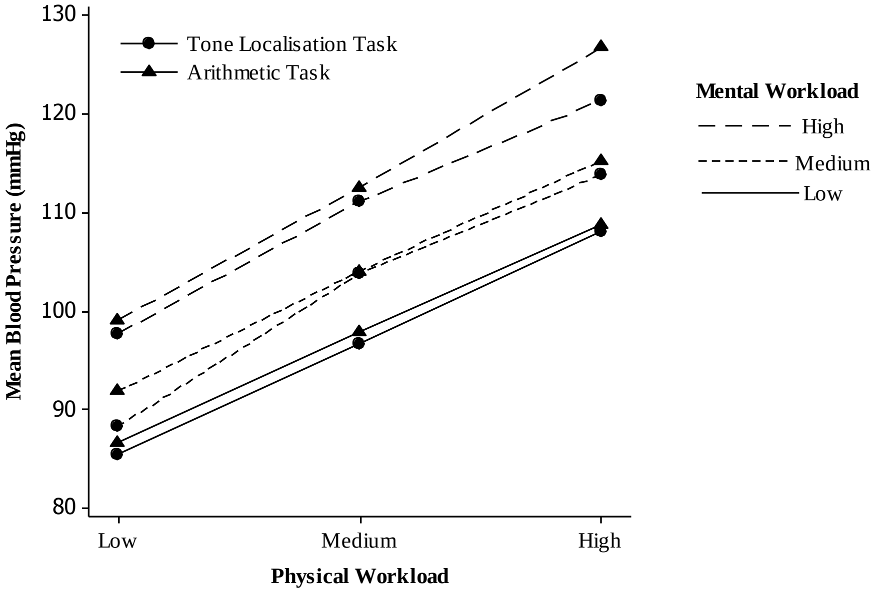


Figure 6.12 Mean blood pressure for both arithmetic and tone localisation tasks under nine levels of physical and mental workload interaction

Gender Differences and Physiological Parameters

In the gender analysis, ANOVA showed that gender had a significant impact on HR (*F*(1,26) = 8.27, *p*<0.05). Females had a higher mean HR than males under all workload interaction conditions in both auditory tasks. However, Tukey's analysis showed no significant differences in HR between males and females in the tone localisation task under any level of workload interaction (*p*>0.05). In contrast, there was a significant difference between genders in the auditory arithmetic task at a medium workload of physical lifting (14% of body mass) × high mental workload (*p*<0.05), and high level of physical workload × high mental workload (*p*<0.05) (See Figure 6.13).

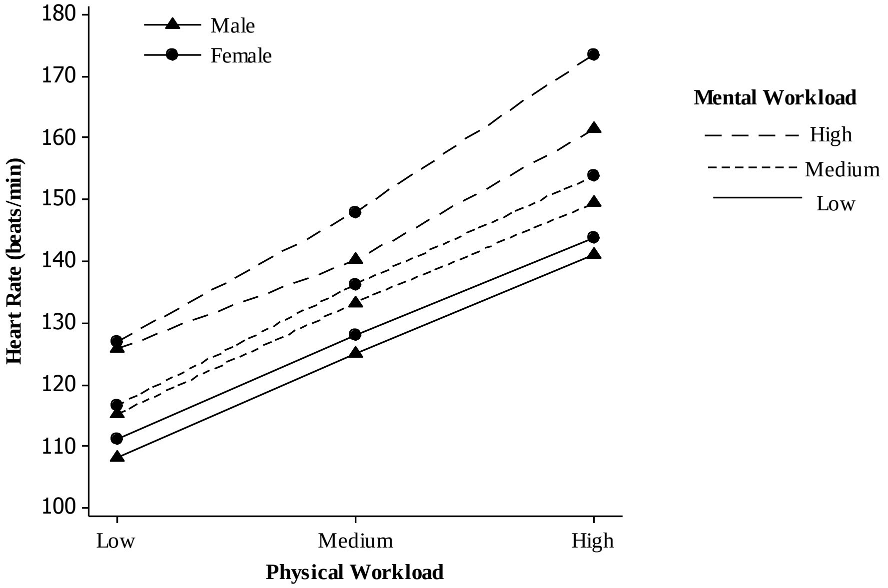


Figure 6.13 Mean HR for males and females in the auditory arithmetic task during physical and mental workload interaction

However, gender did not significantly affect HRV (*F*(1,26)= 3.31, *p*=0.224). The variance analysis showed that the effects of gender on MBP were significant (*F*(1,26) = 13.53, *p*<0.05). The mean blood pressure of females was higher than males in the arithmetic test, but there was no significant difference between genders in the tone localisation task at any level of physical and mental workload interaction (*p*>0.05). However, Tukey's HSD test showed that in the auditory arithmetic task there were significant differences between genders at the medium workload of physical lifting workload × high mental workload and high lifting level of physical workload × high mental workload (*p*<0.05) (Figure 6.14).

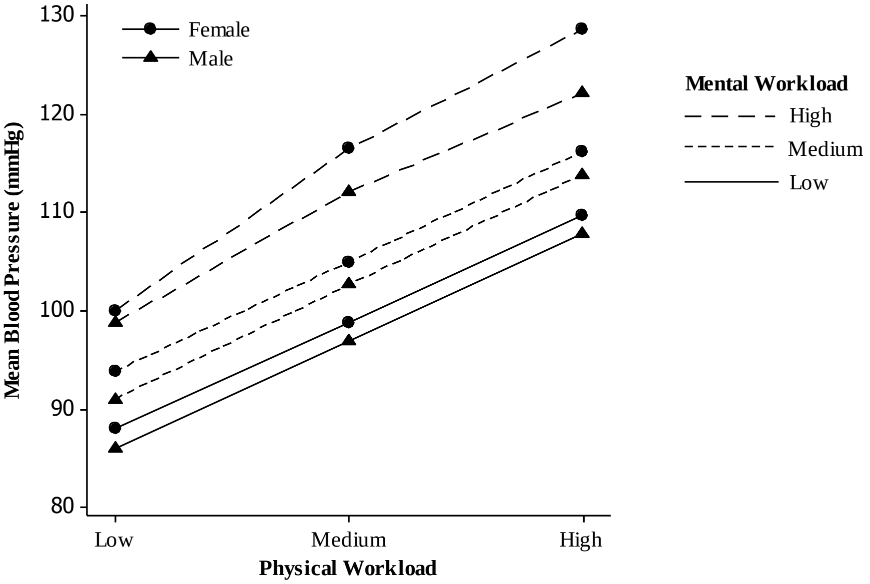


Figure 6.14 Mean of MBP for males and females in the auditory arithmetic task during physical and mental workload interaction

6.4.3 Brain Activity

Regional Cerebral Oxygen Saturation (rSO2)

Mental workload had a significant impact on the percentage of oxygen in the brain (rSO2) (*F*(1.8,47.8) = 1026.39, $p<0.01$) in both task conditions. Physical workload levels in both mental auditory tasks also significantly affected rSO2 (*F*(1.7,44.8) = 558.15, $p<0.01$). Generally, mean rSO2 was significantly increased while mental workload increased and it decreased while physical lifting load increased (Figure 6.15). Moreover, the physical and mental workload interactions had a significant influence on rSO2 (*F*(3.7,94.8) = 19.64, $p<0.05$).

According to the contrast analysis for rSO2, there was a significant difference between mental workload levels for low vs. medium workload and medium vs. high workload ($p<0.01$ for both). In addition, the data analysis demonstrated significant differences between rSO2 at all physical workload levels ($p<0.05$), except at medium and high physical lifting × high mental workload in both arithmetic and tone localisation tasks ($p=0.092$ and $p=0.084$, respectively), (see Figure 6.15). The impact of task type was not significant (*F*(1,26) = 2.11, $p=0.12$).

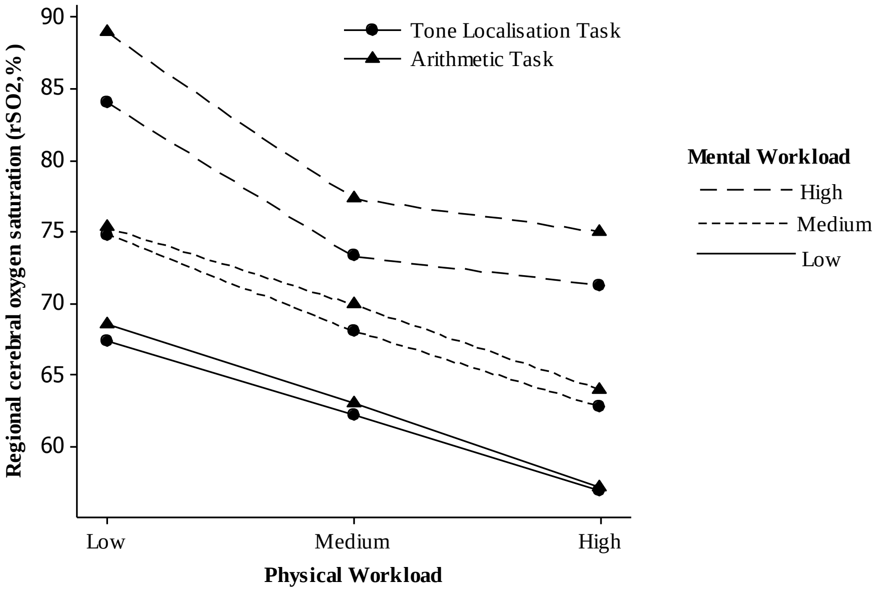


Figure 6.15 Mean of regional oxygen saturation in the brain for both auditory tasks responses against physical and mental workload interactions

Gender Differences and rSO2

The gender variable was not significant (*F*(1,26) = 1.85, *p*=0.239).

6.4.4 Subjective Assessment Tools

Mauchly's test was used to check the assumption of sphericity. The test illustrated that the assumption of sphericity was not met for Borg's scales (CR10 and RPE) and the NASA-TLX scale (*p*<0.05), so the *F*-adjusted was used.

Physical Workload Assessment Tools

The Borg CR10 Scale and RPE scales were implemented to evaluate the perceived physical lifting load in the study. The scores significantly increased when the physical workload increased. In addition, the effect of physical workload on the Borg-CR10 and RPE was significant (*F*(1.7,49.7) = 2013.25, *p*<0.01) and *F*(1.5,38.6) = 954.76, *p*<0.01), respectively. In contrast, the effect of mental workload on both assessment scores was not significant (Borg-CR10, *F*(1.9,50.5) = 1.76, *p*=0.421 and RPE, (*F*(1.7,44.2) = 0.89, *p*=0.875) (Figure 6.16 and Figure 6.17). The interaction of physical and mental workload was not significant on both scales Borg-CR10 and RPE (*F*(4,104) = 0.25, *p*=0.82) and (*F*(4,104) = 0.46, *p*=1.08), respectively .

The effect of task type on the Borg scores was not significant (Borg-CR10, *F*(1,26) = 4.59, *p*=0.87 and RPE, (*F*(1,26) = 3.72, *p*=0.94). However, according to contrast tests, there was a significant difference between the physical workload levels under all levels of workload interaction (*p*<0.01) in the Borg CR10 scale and in the RPE score (*p*<0.01) (Figures 6.16 and 6.17).

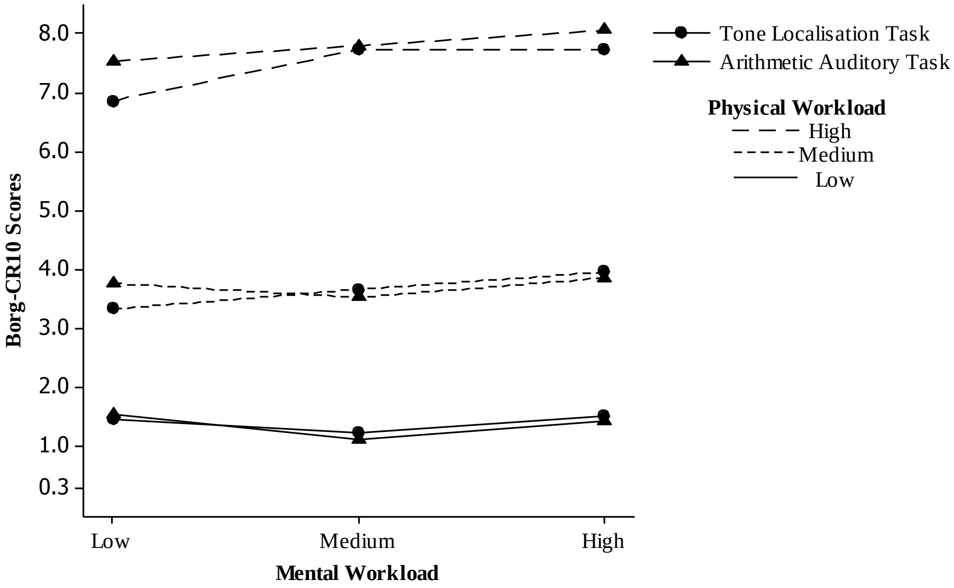


Figure 6.16 Mean Borg-CR10 scores for arithmetic and tone localisation mental tasks against physical lifting and mental workload interaction

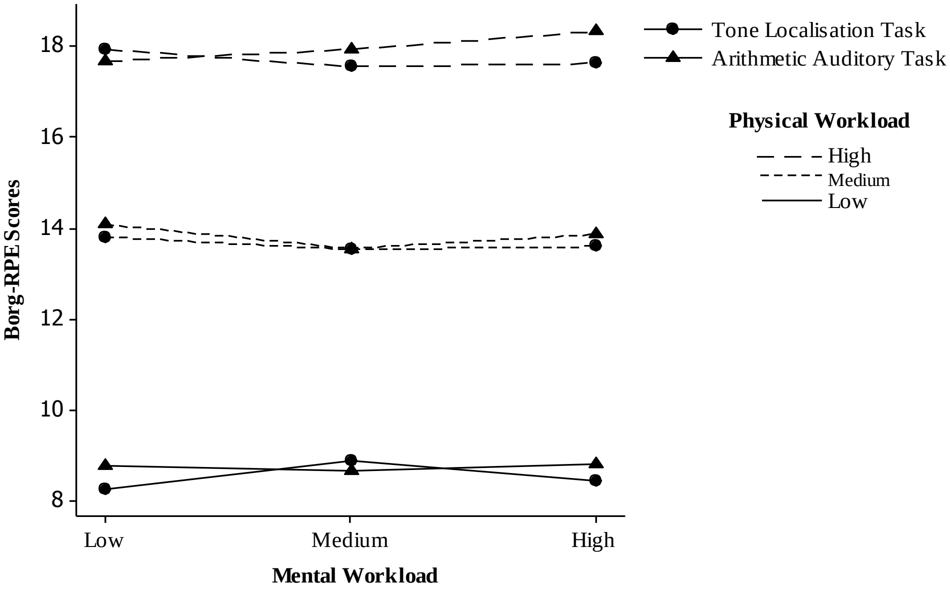


Figure 6.17 Mean RPE scores for arithmetic and tone localisation mental tasks against physical lifting and mental workload interaction

NASA-TLX Assessment Tool

Overall workload on the TLX was calculated by averaging all the dimensions of the NASA-TLX ratings, as noted in Equation (3) in Chapter 4, section 4.4.4. The ANOVA showed that mental workload significantly impacted the NASA-TLX scores ($F(1.7,44.5) = 4123.52$, $p<0.01$). The physical workload factor also had a significant impact on the ratings ($F(1.8,46.7) = 2456.85$, $p<0.01$) (See Figure 6.18). Moreover, the effects of the physical and mental workload interactions on NASA-TLX were significant ($F(3.5,90.6) = 18.27$, $p<0.05$). At a high level of mental workload versus medium and high physical workload the arithmetic task received higher scores ($p<0.05$ for both).

According to contrast analysis for the NASA-TLX ratings, there was a significant difference between the mental workload levels for low vs. medium level and medium vs. high level, ($p<0.01$ for both tasks). In addition, the analysis found significant differences between NASA-TLX scores in physical workload for low physical level vs. medium level and medium vs. high level, ($p<0.01$ for both tasks). The impact of task type was not significant ($F(1,26) = 4.42$, $p=0.075$).

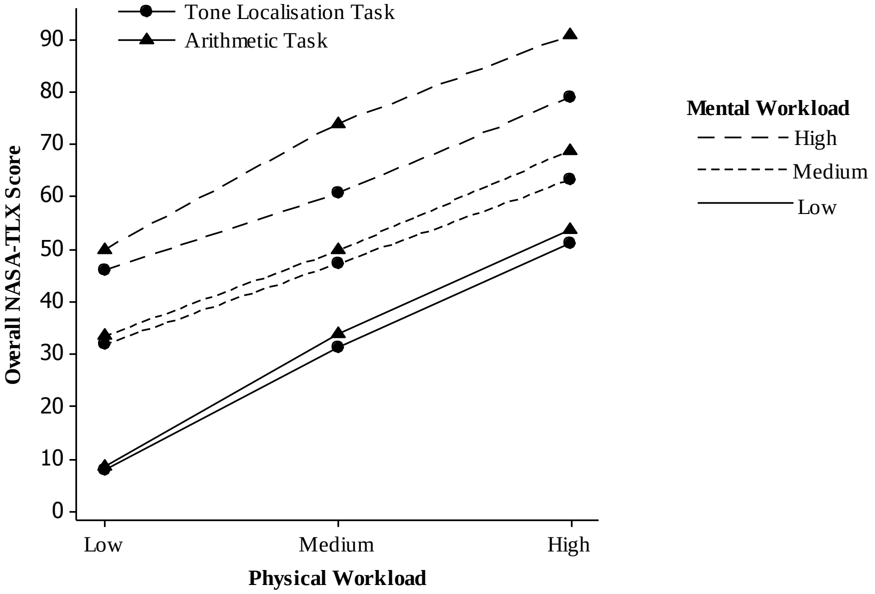


Figure 6.18 NASA-TLX scores for overall workload on both auditory tasks against physical and mental workload interactions

In this section the mental demand (MD) and physical demand (PD) TLX scores were analysed in order to find the effect of physical workload levels on subjective assessment of mental workload. This will provide beneficial information about the impact of physical workload levels on individual judgments about mental workload. In terms of mental demand, the ANOVA analysis showed that the mental workload of both tasks had a significant impact on NASA-TLX ratings ($F(1.6,44.5) = 1146.22$, $p<0.01$). However, the impact of physical loads on mental demand was not significant ($F(1.8,46.5) = 3.17$, $p=0.18$). The effect of physical workload and the interaction was not significant ($F(3.5,96.4) = 1.72$, $p=0.84$). The TLX score increased significantly as the level of difficulty increased (Figure 6.19). The contrasts indicated that there was a significant difference between mental workload levels in arithmetic and tone localisation tasks ($p<0.05$ and $p<0.05$, respectively). However, there were no significant differences between all levels of physical workloads ($p>0.05$). The effect of task type factor on the mental subscale was not significant ($F(1,26) = 1.57$, $p=0.25$).

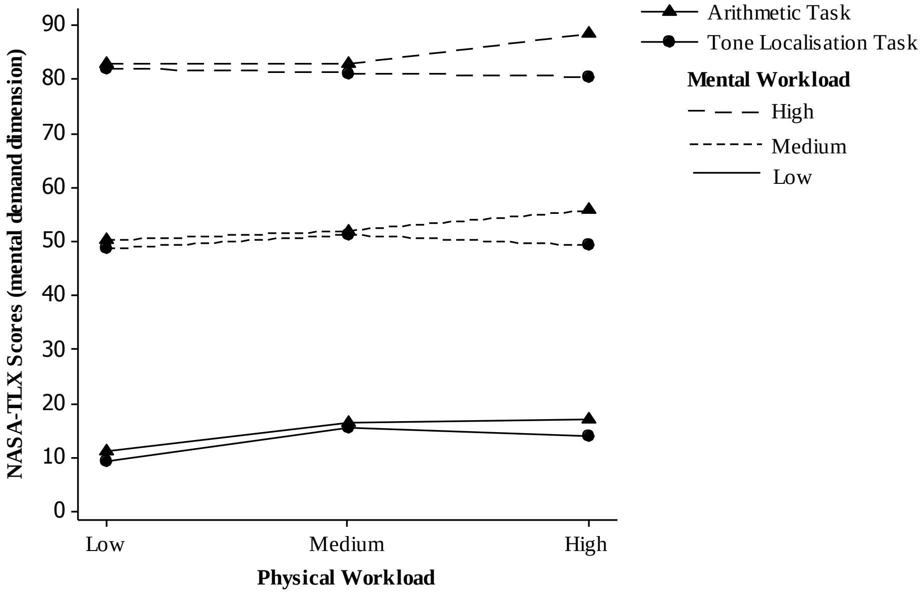


Figure 6.19 NASA-TLX mental demand dimension for arithmetic and tone localisation tasks

In terms of the physical demand dimension, the ANOVA showed that physical workloads impacted significantly on the physical dimension of workload for both tasks in the NASA-TLX ratings (*F*(2,52) = 934.18, *p*<0.01) (Figure 6.20). The impact of mental load on the physical dimension was not significant (*F*(2,52) = 4.33, *p*=0.48). Also, the effect of physical and mental workload interactions was not significant (*F*(4,104) = 0.86, *p*=0.97). However, the contrast tests indicated that there was a significant difference between physical workload levels under all levels of interaction (*p*<0.01).

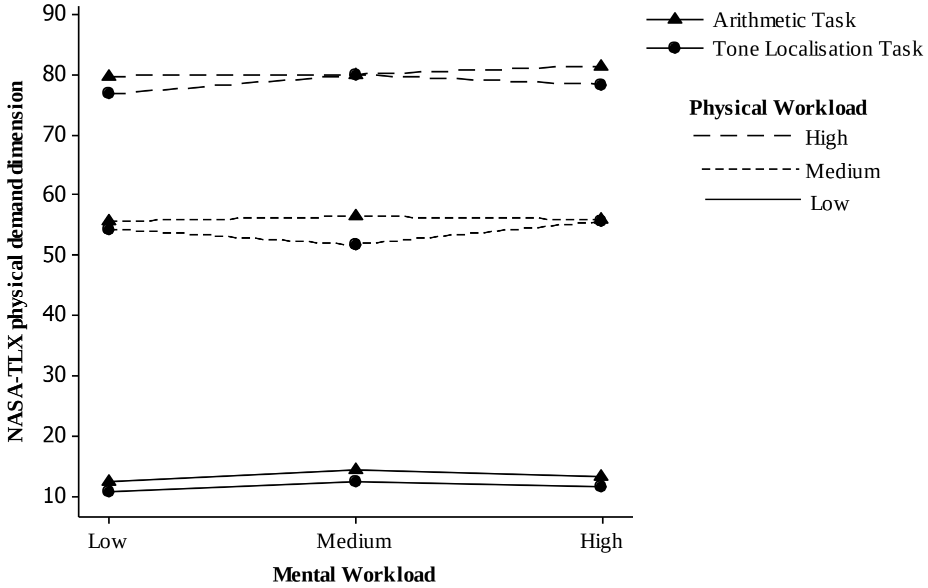


Figure 6.20 NASA-TLX physical demand dimension for arithmetic and tone localisation tasks

Gender Differences and Subjective Assessment Tools

In terms of Borg's scales, the effect of gender was significant on CR10 scores and RPE scores (*F*(1,26) = 13.11, *p*<0.05 and *F*(1,26) = 14.24, *p*<0.05, respectively). Generally, the female rating scores were higher than those of males in both scales under all levels of workload interactions in both auditory task conditions, similar to the results of Chapter 5. Furthermore, Tukey's analysis showed that the females scored significantly higher than males in both Borg's ratings at medium and high levels of physical lifting workloads (14 and 20% of body mass) in both mental task conditions. Figures 6.21 and Figure 6.22 present the gender differences at medium and high levels of physical workload in the arithmetic task (*p*<0.05 and *p*<0.01, respectively). In addition, in the tone localisation task, the same differences between genders occurred at medium and high workloads of physical lifting loads in both

CR10 and RPE scales: ($p<0.05$ and $p<0.01$, respectively). The figures for Borg scale scores in the tone localisation task are not illustrated since they are approximately the same as those of the arithmetic task.

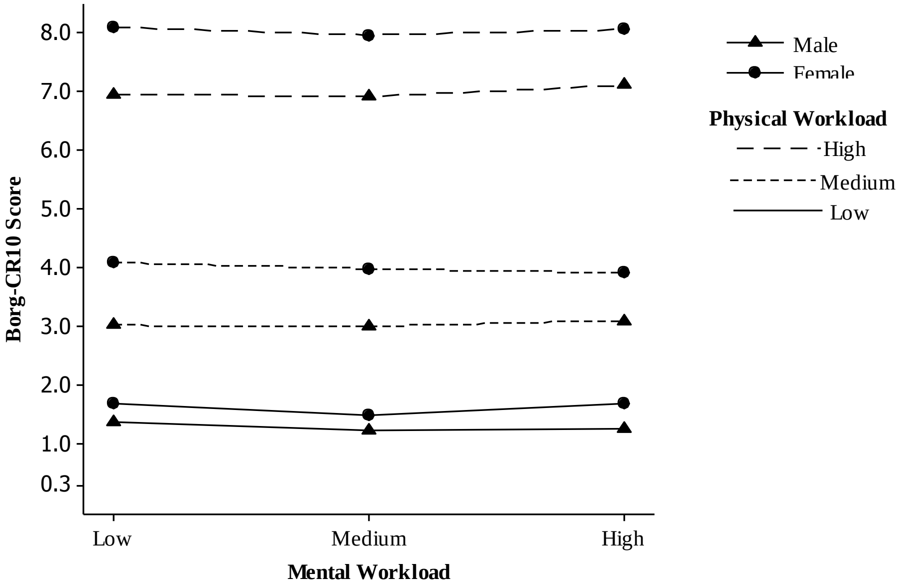


Figure 6.21 Mean Borg-CR10 scores for males and females in the arithmetic task during physical and mental workload interaction

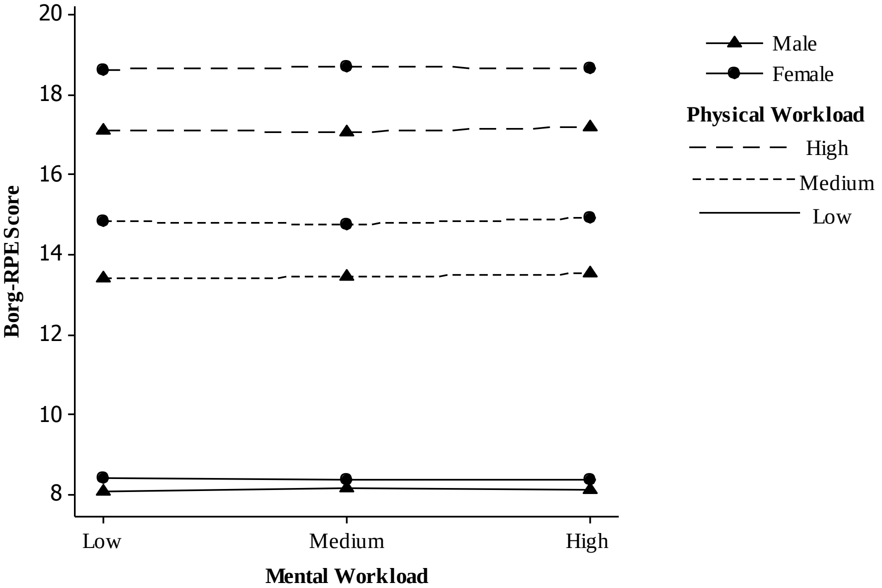


Figure 6.22 Mean Borg-RPE scores for males and females in the arithmetic task during physical and mental workload interaction

In term of the NASA-TLX and gender differences, the effect of gender was not significant (*p*=0.112). Also, the impact of gender on mental and physical dimensions was not significant (*F*(1,26) = 1.79, *p*=0.132) and (*F*(1,26) = 2.34, *p*=0.085).

6.4.5 Correlation between Objective and Subjective Variables

Pearson's correlation (r) was used to identify the correlation between the objective measures and subjective measures of physical and mental workload interactions for the arithmetic and tone localisation tasks, as illustrated in Table 6.5. This correlation was used to find out how the performance variables related to the physiological measures (i.e., positive or negative correlation with NASA-TLX and Borg's scales). Generally, the objective variables were significantly correlated with overall NASA-TLX scores in both tasks, except the HRV scores. In addition, accuracy was significantly correlated with physiological variables and subjective assessment tools (i.e., NASA-TLX, Borg-CR10 and Borg-RPE). Accuracy and time of task were significantly related to NASA-TLX rating scores ($r = -0.52$, $p < 0.05$ and $r = 0.41$, $p<0.05$, respectively). As expected, rSO2 was significantly negatively correlated with task time ($r = -0.39$, $p<0.05$), whereas it was positively correlated with overall workload on the TLX.

Table 6.5 Pearson's correlation coefficient matrix (r) for the objective and subjective variables of workload interactions

Variables		HRV	MBP	rSO2	Time	Accuracy	NASA-TLX scores	RPE	Borg CR-10 scores
HR		**-0.42**	**0.46**	**-0.34**	**0.60**	**-0.39**	**0.59**	**0.32**	**0.41**
	p-value	**0.01**	**0.01**	**0.03**	**0.01**	**0.01**	**0.01**	**0.04**	**0.01**
HRV			**0.42**	0.01	0.07	**0.51**	**-0.44**	0.17	0.20
	p-value		**0.01**	0.48	0.36	**0.01**	**0.01**	0.18	0.15
MBP				**-0.34**	**0.42**	**-0.55**	**0.59**	**0.42**	**0.48**
	p-value			**0.03**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
rSO2					**-0.39**	-0.22	**0.31**	0.30	0.29
	p-value				**0.02**	0.12	**0.04**	0.06	0.06
Time						-0.20	**0.41**	0.11	0.34
	p-value					0.15	**0.01**	0.29	0.03
Accuracy							**-0.53**	**-0.38**	**-0.44**
	p-value						**0.01**	**0.02**	**0.01**
NASA-TLX scores								**0.37**	**0.41**
	p-value							**0.02**	**0.01**
RPE									**0.61**
	p-value								**0.01**

***bold represents the significance value *p*< 0.05**

6.4.6 Main Findings

Table 6.6 Main Results of the Third Experiment

Hypotheses	Results
1- The participants' best performance will occur at medium physical lifting × medium mental auditory workload interactions.	Accuracy and time of task significantly worsened ($p<0.05$) at medium levels of physical (14% of body mass) and mental workload interactions in both mental auditory tasks. *The hypothesis was rejected.*
2- The participants' worst performance will occur with a high physical lifting and high auditory mental workload interactions due to the high level of arousal.	In auditory mental tasks (arithmetic and tone localisation tasks), the significantly worst accuracy and time of task were observed ($p<0.05$). The hypothesis was not rejected.
3- Participants' performance will be worse with low physical lifting workload × low auditory mental workload interactions due to a low level of arousal.	The performance (accuracy and time of task) was significantly better ($p<0.05$) at a medium physical workload (14% of body mass) and low auditory mental workload. *The hypothesis was not rejected.*
4- Participants will perform better at medium physical lifting × low auditory mental (verbal and spatial) workload interactions due to an increased level of arousal by physical workload.	Performance was better in both auditory mental task conditions at low physical workload × low auditory mental workload interactions ($p<0.05$). *The hypothesis was rejected.*
5- The participants' best performance will occur with medium physical lifting× low auditory mental workload. The participants will perform better with medium physical lifting × medium auditory mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of the physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.	The performance (accuracy and time of task) significantly worsened ($p<0.05$) at a medium physical workload (14% of body mass) and medium mental workload but was better at medium physical workload and low mental workload. Increasing levels of physical workloads significantly increased the oxygen delivered to the brain by reducing rSO2 (percentage of oxygenation changes) ($p<0.05$). *The hypothesis was rejected for performance at medium workload interactions but was not rejected for other condition.*
6- The worst performance will occur with high physical lifting and high auditory mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by a high auditory workload since the increasing level of auditory mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the auditory workload.	The performance worsened at high physical load × high auditory mental workload interactions because of the reduction in brain oxygen since rSO2 was significantly increased at a high auditory workload ($p<0.05$). Moreover, there was no significant decrease in rSO2 at medium and high physical levels under medium and high mental workloads in either task type ($p<0.05$). *The hypothesis was not rejected.*
7- No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level by physical activity and increased oxygen delivered to the brain.	There were no significant differences between the genders in the accuracy of auditory tasks. Females spent more time than males in arithmetic tasks at high physical and medium mental workloads ($p<0.05$). *The hypothesis was rejected for accuracy but was not rejected for time of task in the arithmetic task at the medium mental workload.*
8- At high levels of physical and mental workload combinations, men are expected to perform better than women in the auditory-spatial task, whereas women will perform better in the auditory-verbal task due to the physical workload capacity differences between genders and the high level of arousal.	No gender differences were observed in the tone localisation task. Females spent more time than males in arithmetic tasks at high physical and medium mental workload ($p<0.05$). Gender differences appeared in HR and MBP at high level of physical workload interaction with mental workloads in the arithmetic task. *The hypothesis was rejected.*

6.5 DISCUSSION

These experiments were carried out to answer these hypotheses as stated in section 6.1:

1. ***The participants' best** performance will occur at medium physical lifting × medium mental auditory workload interactions.*
2. *The participants' worst performance will occur with a high physical lifting and high auditory mental workload interactions due to the high level of arousal.*
3. *Participants' performance will be worse with low physical lifting workload × low auditory mental workload interactions due to a low level of arousal.*
4. *Participants will perform better at medium physical lifting × low auditory mental (verbal and spatial) workload interactions due to an increased level of arousal by physical workload.*
5. *The participants' best performance will occur with medium physical lifting× low auditory mental workload. The participants will perform better with medium physical lifting × medium auditory mental (verbal and spatial) workload interactions due to increased oxygen (blood flow) delivered to the brain caused by the medium physical workload. Since increasing the level of the physical workload will supply more oxygen to the brain, brain activation will decrease with a concurrent decrease in rSO2.*
6. *The participants' worst performance will occur with high physical lifting and high auditory mental workload interactions due to the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high auditory workload since the increasing level of auditory mental load leads to an increased level of rSO2, which means an imbalance between the oxygen available to the brain and the amount that it needs to meet the auditory workload.*

Previous research studies on the separate impacts of physical and mental auditory workload on human performance have been carried out (Audiffren et al., 2008). However, as mentioned in section 6.1, the effect of lifting physical loads has not been carried out previously in investigating the effect of physical and mental auditory workload interactions on performance (Astin and Nussbaum 2002). One study investigated the effect of physical and mental demands on a simple mathematical task

(DiDomenico and Nussbaum, 2008, 2011) but neither study considered the effect of workload interactions on attentional resources along two of Wickens' (2008) dimensions: input modality (visual vs. auditory), and processing code (verbal vs. spatial). Therefore, no study has examined the impact of different levels of physical lifting and mental workload interactions on spatial auditory tasks. This study was developed to examine the mechanism of the physical lifting task and mental workload interactions with two codes of auditory attentional resources (verbal and spatial) through increasing levels of physiological arousal. In addition, this research examined whether the physical workloads impact in shrinkage of auditory attentional resources caused by the low level of mental workload due to the low arousal. Furthermore, the gender factor was considered in this study to understand the differences between males and females in performing auditory tasks while exercising, since according to Yagi et al. (1999), gender differences while performing physical and mental tasks under different levels of interaction have received less attention. In addition, it aimed to investigate how physical workload leads to better auditory performance by supplying more oxygen to the brain and reducing brain activation due to auditory workloads.

6.5.1 Performance

Generally, the performance of participants worsened with increased difficulty of the physical and mental workload in both the arithmetic and tone localisation tasks. The first hypothesis in this experiment was rejected since; the medium physical lifting workload (14% of body mass) did not lead to best performance at medium mental workload. However, the low (8% of body mass) and medium (14% of body mass) physical lifting levels led to better performance at the low mental workload in both auditory tasks. These results were not consistent with those of DiDomenico and Nussbaum (2008), who found no impact of a lifting activity on a simple arithmetic task. It may be that the types of mental auditory tasks used in the current study are more complex than those used by the other researchers. There was no significant difference in accuracy between the low and medium physical lifting loads at a low mental workload. These results support the hypothesis that a medium physical level would lead to better performance at low mental demand. This may be because physical activity led to increased physiological arousal, so the auditory information process was better, which is consistent with the results of previous papers (Audiffren et al., 2009; Mozrall and Drury, 1996). Furthermore, the current results indicated that the low lifting load led to better task times at medium mental auditory workload, since there were no significant differences between task time at low and medium mental demand under a low lifting load in either the arithmetic or tone localisation tasks. Furthermore, the time taken to complete both tasks was better at a medium physical workload and low mental workload. In contrast, as found in Chapter 5 (see the pilot study description in section 5.2.1); in the resting condition there was a significant difference between low and medium mental demand in both the arithmetic and tone localisation tasks. This may be because the physical activity supplied more blood and oxygen to the brain during low and medium physical lifting, facilitating information processing. This was the assertion of Antunes et al. (2006). Unexpectedly, the medium lifting workload (14% of body mass) led to worse performance in both mental tasks at a medium mental load, which may be because the lifting task and auditory mental task interaction were more complex, as shown in similar results in Chapter 5 (see section 5.4.1). Therefore, the first hypothesis in this experiment, which assumed the best performance will occur at medium workload interaction conditions, was rejected. It is possible that the visual cognitive tasks were easier than the auditory tasks, because the individuals needed to employ a more intensive cognitive process to complete the auditory tasks (Yagi et al., 1999). Generally, there were no differences between the different physical tasks used in the current chapter (lifting boxes) and in Chapter 5 (stationary bicycle ergometer-) since most of the effects of physical and mental workload on the accuracy and time of auditory tasks were the same.

The overload level of workload interactions (i.e., 20% of body weight × high mental auditory load) led to the worst performances in both the arithmetic and tone localisation tasks. Heavy lifting has a repetitive work impact on physical capacity and places stress on verbal auditory attentional resources rather than spatial resources, so it reduces attention and increases errors (Stoessel et al., 2008). This was consistent with previous studies that found that increasing the number of speakers activated in the mental demand test led to poorer accuracy (Lee, 2001). Similar results were found previously by Yagi et al. (1999), who found a decrease in the accuracy of an auditory P300 task due to increased physical activity, because of the increased level of arousal. Pearson’s correlation test showed a moderate positive correlation between time and HR and MBP ($r = 0.60$, $p < 0.05$ and $r = -0.42$, $p < 0.05$), respectively, which means that time increased under high values of HR and MBP due to increased levels of physiological arousal caused by increasing levels of physical and mental workload interaction.

The current results showed that the auditory arithmetic condition was more difficult than the tone localisation task in the pilot study (see Chapter 5, section 5.2.4). The participants’ accuracy under the arithmetic condition was lower than in the tone task, whereas there were no significant differences between the two tasks in accuracy concurrent with the physical lifting task. This may be because the physical activity led to better accuracy of both tasks by increasing the arousal level and transporting more oxygen to the brain. However, task time showed significant differences between the two mental auditory tasks with high lifting physical workload × high mental workload, possibly because the arithmetic task was more difficult. This may be because the workload levels used in the tone localization task were easier than the levels of difficulty in the auditory arithmetic task. In addition, in the arithmetic auditory task, participants needed to engage in complex information processing, i.e., transferring numbers to words and then performing the calculation process and recalling data from long-term memory. Also, in the pilot study (see Chapter 5, section 5.2.4) at high mental workload, the arithmetic task consumed more time than the tone localisation task. Again, this could be because the auditory mental tasks were more difficult than the visual cognitive tasks, since they required more executive function processes such as recalling the information from long-term memory and requiring more time to allocate information for the efficient allocation of attentional resources (Yagi et al., 1999). In addition, the physical exercise may have led to better performance in the visual tasks more than the auditory tasks.

6.5.2 Physiological Parameters

Numerous physiological variables were recorded in this study to support the results, because these variables are very sensitive to physical and mental demand changes (Fredericks et al., 2005). In general, these variables were affected by the difficulty changes in the lifting physical task and mental auditory tasks.

As expected, the HR, HRV, and MBP physiological variables increased as the physical lifting and mental auditory tasks increased. According to the results, heart rate and mean blood pressure increased significantly when the physical lifting workload increased, and it increased significantly when the mental auditory task workload (both arithmetic and tone localisation tasks) increased. This increase in blood pressure (systolic blood pressure) was observed previously by Fredericks et al. (2005), who reported that increasing the level of difficulty of a mental mathematics task and riding increased the strain on the cardiac system, which led to increased heart rate and blood pressure. This suggests that increasing the level of the lifting task led to increased physiological arousal. Furthermore, previous authors have shown that high levels of physical demand and cognitive auditory tasks increased the stress on the cardiovascular system, leading to an increased heart rate (Audiffren et al., 2009; Kamijo et al., 2004). In this research, the heavy lifting manual task impacted the physiological state of the individual, which can lead to performance decrements (Ayoub and Dempsey, 1999), so high levels of workload interaction cause stress on attentional resources and increased arousal level. This may be because the performance of the participants decreased at high levels of interaction.

The interesting results of the current chapter indicate that the effect of physical and mental workload interactions was significant on HR and MBP, since there was no significant difference between HR in the tone localisation task low physical lifting workload (8% body mass) × low mental workload and low physical lifting workload × medium mental workload. This may be because the participants did not consume a significant time to complete the tone localisation task at low physical and medium mental workload interactions which was same as the time used for low physical and low mental workload interactions. However, in the baseline condition (see Chapter 5, pilot study in section 5.2.1), there was a significant difference between HR at the low and medium mental workload levels in the tone localisation task. In addition, there were no significant differences between MBP at the low physical lifting workload × low mental workload and low physical lifting workload × medium mental workload in the tone localisation task. That may be because the participants did not consume a significant time to complete the tone localisation task at low physical and medium mental workload interactions which was same as the time used for low physical and low mental workload interactions. However, task times in both auditory tasks at low and medium mental workload were better at the low physical lifting load since there were no significant differences between low and medium mental workload levels at low physical lifting task. In contrast, there were significant differences between time in the low and medium mental workloads levels in the baseline condition. This may be because the increasing level of arousal caused by physical activity led to better task times. As mentioned in the previous section (6.6.1), the positive impact of low and medium physical load (8% and 14% of body mass) on accuracy and task times in both auditory tasks at low mental workload may be because the physical workload increased the physiological arousal level, so the differences in performance with the low and medium physical lifting for the low workload mental auditory task were not significant. Audiffren et al. (2009) stated that an incremental increase in physical activity improved performance due to an increased level of arousal, so performance during physical activity was better than in the rest condition. According to Pearson's correlation, the HR and MBP variables were moderate significantly correlated with accuracy and time. This indicates that variations in physiological arousal due to physical and mental workload interactions significantly altered the task time and accuracy.

Furthermore, the effect of the physical and mental workload interactions was significant on HR and MBP. There were significant differences between mental arithmetic workloads while interacting with physical loads, which may be because the auditory arithmetic task used in this chapter was more complex and required more time than the tone localisation task. The arithmetic task performed concurrently with the physical lifting task resulted in higher HR and MBP than the tone localisation task, but there were no significant differences. The differences between the two tasks in HR and MBP occurred with high physical workload levels interacting at medium and high mental workloads, similar to the results in Chapters 4 and 5. However, the effect of the task type factor was not significant on HR and MBP.

HRV showed an increasing level of physical and mental workload interaction. It was interesting that HRV decreased as the mental auditory workload increased in both the mental arithmetic and tone localisation tasks. In contrast, increasing physical lifting levels led to increased heart rate variability. This result was observed previously by Hwang et al. (2008), who found that increasing levels of a monitoring workload in a control room at a nuclear factory led to heart rate variability decrements. In addition, according to Rennie et al. (2003), increasing levels of physical activity from walking to jogging produced increased HRV values. The effect of physical and mental workload interactions on HRV was significant. There were no significant differences between the arithmetic and tone localisation tasks in HRV under low and medium physical workload interaction with low and medium mental workloads. In contrast, there was a significant difference between the two tasks in HRV at rest (see pilot study in section 5.2.1). The auditory arithmetic task yielded a significantly lower value of HRV under high physical load (20% of body mass) interactions with medium and high mental loads. This was expected because the heart rate variability measure is a very sensitive physiological variable to high workload changes in complex mental task situations (Veltman and Gaillard, 1998). The effect of the task type factor was not significant on HRV.

6.5.3 Brain Activity

Regional oxygen saturation (rSO2) in the frontal region of the brain was measured to reflect the percentage of brain oxygenation during physical and mental auditory workload interactions. Generally, the increasing level of mental workload in both the auditory tasks influenced brain activity as reflected by increases in rSO2. This means the amount of oxygen available in the brain was not equal to the amount of oxygen needed to meet the demands of either auditory task. Similar results were found by Kashihara et al. (2009), who mentioned that an increased level of auditory mathematical task led to increased oxygenation changes in the brain, so performance decreased. In contrast, rSO2 decreased significantly as the physical lifting load increased. However, the effect of physical workload on rSO2 at high levels of physical and mental workload interactions was not significant in either auditory task, since the differences between rSO2 at medium and high levels of physical load under a high level of mental auditory workload were not significant. This may be because, at a high level of physical activity, the muscles require more oxygen than the brain before the stage of fatigue, so the amount of oxygen transported to the brain declines (Perrey et al., 2010).

However, the physical load increased the percentage of blood flow to the brain, so the amount of oxygen delivered to the brain increased and the oxygenation changes decreased. Auditory information processing was assisted by creating a balance between the availability of oxygen in the brain and the amount of oxygen needed to meet the demands of the information process. This explains why the performance of participants was better in auditory tasks performed concurrently with physical activity than in the baseline condition. This was consistent with Antunes et al. (2006), who stated that physical activity led to increased amounts of oxygen being transported to the brain, so physical activity improves reaction time in an auditory task compared to the rest condition. As mentioned in section 6.6.1, the accuracy of participants in both auditory tasks improved under low and medium physical loads versus a low mental workload. There were no differences between task times under low and medium mental auditory levels, whereas in the baseline condition there were significant differences between the levels in both auditory tasks. This may be because the amount of oxygen in the brain and the quantity of oxygen needed to complete the tasks were equal because the physical activity transported more oxygen to the brain and the mental load was not high.

Also, the findings demonstrated that the effect of the task type factor (arithmetic or tone localisation task) on rSO2 was not significant. This may be due to the positive impact of the physical workload on brain activation while performing the tasks, so the effect of mental auditory workload on increasing rSO2 was impacted by physical activity since more blood and oxygen were transported to the brain, thus the differences between tasks disappeared. Pearson's correlation test showed a weak negative correlation between oxygenation changes and HR and MBP (r = -0.34, p < 0.05 and r = -0.34, p < 0.05), respectively. This may be because increasing the level of physical workload led to a decrease in rSO2, which means that the increase in brain oxygenation changes due to a high mental workload decreased because of physical activity. This may account for the improvements in time and accuracy at moderate physical levels and low mental auditory demand in both tasks. In addition, rSO2 illustrated that the brain oxygenation variation correlated with changes in physical demand, just as with auditory mental demand.

6.5.4 Subjective Assessment Tools

Physical Workload Assessment Tools

As expected, both Borg scales that were used in the current study were impacted by the physical lifting workload but were not sensitive to mental workload difficulty changes in both the mental arithmetic auditory task (verbal task) and the tone localisation task (spatial task). The participants scored the task highly when the physical workload increased in both CR10 and RPE. In addition, numerous previous studies have found that increasing Borg scores for CR10 and RPE are associated with increasing physical loads in tasks such as lifting boxes (see DiDomenico and Nussbaum, 2008; Li et al., 2009) and stationary bicycle ergometer riding (see Borg, 1998; Borg, 1985; Fredericks et al., 2005; Pontifex et al., 2009). Furthermore, according to DiDomenico and Nussbaum (2008), the scale ratings are sensitive to changing physical lifting task levels; however, these scales are not sensitive to mental auditory arithmetic task demand. In addition, the effect of physical and mental workload interactions was not significant (p=0.82). However, distinctly varying Borg CR10 and RPE scores were found for the different physical lifting levels. There were no substantial changes in Borg scores due to mental auditory workload changes. This indicates that changes in mental auditory levels do not impact physical workload subjective assessments.

The scores were not found to be significant between the ratings in the two mental auditory tasks (tone localisation and arithmetic) since they were not sensitive to the mental workload changes. Furthermore, the Pearson correlation indicated a moderate positive correlation ($r = 0.61$, $p < 0.05$) between CR10 and RPE scores, which means that the increasing score of CR10 is associated with an increased RPE score. Also, 37% of the variation in the CR10 score can be accounted for by the variation in the RPE score. Both scores were significantly linear and increased with an increase in physical workload since HR increased. Hence, any elimination for either score would not impact the research findings negatively.However, the Borg-CR10 and RPE scores were significantly correlated with HR, MBP, accuracy, and TLX scores, indicating that the variations in both scale scores were significantly altered by physical load difficulty levels and physiological arousal level.

NASA-TLX Assessment Tool

In terms of mental demand and the physical dimension in TLX, as expected, the NASA-TLX was sensitive to mental auditory workload difficulty levels for the arithmetic and tone localisation tasks, similar to the results described in Chapter 5 in section 5.6.4.2. In addition, as expected, the present study showed a significant sensitivity to difficulty changes between mental workload levels (low, medium, and high) in both the tone localisation and arithmetic tasks. The results of the NASA-TLX rating were consistent with the physiological measures. The results of the data analysis were consistent with previous studies that found that the NASA-TLX was sensitive to changes in mental demand difficulties (Colle and Reid, 1998; DiDomenico and Nussbaum, 2008; Fredericks et al., 2005; Hwang et al., 2008; Perrey et al., 2006; Rubio, 2004). However, the results showed that the effect of physical level on the mental demand dimension score was not significant. This means that the perceptions of the participants with respect to the mental auditory workload were not affected by the physical load in either task. In addition, that suggests the physical lifting task did not affect participants’ judgments towards mental auditory task workloads, which means that individuals perceived the effect of mental cognitive loads on the mental demand dimension more than physical load demands. The physical demand subscale was influenced by physical level changes, whereas it was not altered by mental workload levels. This is similar to the results in Chapters 4 and 5, which indicated that each dimension was impacted by the level of demand; in short, the mental auditory demand levels did not affect participants' judgment of the physical dimension.

Furthermore, in the overall TLX scores, the current study concluded that the NASA-TLX rating was sensitive to physical and mental workload increases, since the effect of physical lifting load changes on the overall scores was significant, as it was for the impact of mental auditory demand on the scores. This is because the TLX includes a physical demand dimension and was included in the calculation of the overall assessment value. The overall TLX score increased significantly as workload interactions increased. DiDomenico and Nussbaum (2008), Fredericks et al. (2005), and Perrey et al. (2006) used the NASA-TLX questionnaire to evaluate the impact of different levels of physical activities on cognitive processes and determined that the rating scores increased as the physical demand was associated with the mental demand. Furthermore, the effect of physical task levels may also affect the other TLX dimensions, which can be influenced by physical task workloads since the performance and time dimensions were affected by the physical task levels. However, the high overall TLX score was associated with a high physical level, as it was with high mental auditory task levels. Similarly, Chapters 4 and 5 showed that the overall TLX score was associated with a high physical cycling level performed concurrently with high mental visual and auditory demands. Therefore, this study suggests that the NASA-TLX score is valuable as a multi-dimensional assessment technique. Finally, the analysis of the present study showed that the impact of the overall TLX score on the task type factor (arithmetic auditory and tone localisation task) was not significant. Notably, the results found a significant moderate correlation between the TLX overall workload scores and the CR10 ratings ($r = 0.41$, $p < 0.05$), although the correlation between TLX and RPE was weak significance ($r = 0.37$, $p < 0.05$). Thus, whilst there is some redundancy between the TLX and Borg's ratings for physical tasks, there are clearly still some significant elements of each of these complex subjective constructs that are not being accounted for in the other.

6.5.5 Gender Differences

7. *No gender differences are expected at low and medium levels of physical and mental workload combinations due to incremental increases in arousal level by physical activity and increased oxygen delivered to the brain.*

8. *At high levels of physical and mental workload combinations, men are expected to perform better than women in the auditory-spatial task, whereas women will perform better in the auditory-verbal task due to the physical workload capacity differences between genders and the high level of arousal.*

Gender Differences and Performance

In terms of gender differences in accuracy and task time, the differences between men and women in accuracy in the auditory tasks were not significant. In addition, the differences between genders in task time in the tone localisation task were not significant. In contrast, in the arithmetic task, women spent more time than men at a high level of physical load versus high mental demand and at medium physical load against high mental workload. This was consistent with the previous chapter's results (see Chapter 5, section 5.5.1) and the reason for that may the difference between men and women in maximum physical strength (Yagi et al., 1999) together with the possibility that the arithmetic task used in the current experiment was more complex than the tone localisation task.

Gender Differences and Physiological Parameters

At a high mental workload level versus medium and high physical workloads, significant differences between genders occurred in HR and MBP in the auditory arithmetic task. At these levels of physical and mental workload interactions, men were observed to a have lower HR and MBP mean than women in the auditory mental arithmetic task condition. This may be because the women spent more time than men to complete the arithmetic task while carrying out the lifting task. Lindbeck and Kjelleberg (2001) mentioned that there was a significant difference between MBP and HR in men and women in manual lifting tasks because men's maximum strength is greater than that of women, so the maximum physical capacity of women may be influenced by the fact that their physical activity was greater than that of men under the same task conditions. Also, it is possible that the stress of the impact of physical activities affects the physical capacity of women more than men, such that, as mentioned by Borg (1998), the cardiac system of women is affected more by the perceived physical workload than men. This is consistent with Yagi et al. (1999), who found that women exhibited higher HRs than men while performing an auditory reaction time task at a high level of physical activity. In HRV, there were no significant differences between men and women in the two auditory task conditions. However, there was no significant difference between males and females in conducting the tone localisation task concurrently with the lifting task. That may be because the tone localisation task was relatively simple.

In terms of gender differences and rSO2, there were no significant differences between men and women in either auditory task performed concurrently with the physical lifting task. This could be because the physical workload transported more blood and oxygen to the brain during performance of the auditory tasks (Antunes et al., 2006; Perrey et al., 2009), which may have led to reduced differences in oxygenation changes in the brain between genders. In addition, the differences between genders in brain oxygenation depend on the type of mental task. Gur et al. (2000) found that increased brain oxygenation in visual-spatial and verbal-cognitive functional activity was associated more with women than with men.

Gender Differences and Subjective Assessment Tools

In term of Borg’s scales (CR10 and RPE), women scored higher in both scales for perceived physical lifting load, and significant differences were observed at medium and high physical lifting workloads. These results confirmed those of Borg (1998), who mentioned that there were significant differences between genders in RPE scale rating and that women scored higher on RPE at a high-level physical load. In terms of the NASA-TLX score, the analysis showed that the difference between men and women was not significant.

6.6 CONCLUSION

Multitasking physical and mental workloads had an impact on individuals' auditory performance. This chapter aimed to evaluate the influence of physical lifting and mental auditory workload interactions on verbal (arithmetic) and spatial (tone localisation) auditory tasks. A box-lifting physical task was used instead of a stationary bicycle-ergometer task to simulate a product assembly task in a factory; this physical task is more applicable to the real domain than the others. Furthermore, auditory tasks were used in this experiment, since it is difficult to set up visual tasks to be performed concurrently with a lifting task.There was evidence that low and medium physical lifting workloads (8% and 14% of body mass) led to better accuracy at low mental workloads in both auditory task conditions. This may be due to an incrementally increased level of physiological arousal and because more oxygen was transported to the brain, since increasing levels of physical activity produce low oxygenation in the brain by reducing rSO2. Moreover, the better task times occurred at low and medium mental workloads with low physical lifting load conditions; there was no significant difference between times at these mental levels under low physical loads. This did not support the hypothesis that performance would worsen with low physical and mental workload interactions. However, the results proved the hypothesis that medium physical workload would lead to better performance at low mental workload in both auditory tasks. In contrast, at baseline, there was a significant difference between low and medium mental loads. Physical workload led to increased physiological arousal, which led to better cognitive auditory information processing. Overloaded physical lifting and mental auditory workload interactions led to the worst performance. Therefore, this satisfied the hypothesis that overloaded workload interactions would lead to the worst performance due to the high level of arousal and the reduction in the amount of brain oxygen (low blood flow) delivered to the brain caused by the high auditory workload. This indicated an imbalance between the oxygen available to the brain and the amounts of oxygen it needed to meet the auditory workload.

However, there was a negative impact of high physical (20% of body mass) and mental auditory workloads on the arithmetic task time, since at this level of workload interaction the arithmetic task took more time than the tone localisation task, similar to the baseline condition. This may be because the arithmetic task used in this experiment was more complex than the tone localisation task. The results were consistent with the findings in Chapter 5, which indicated that the arithmetic task was more complex than the tone localisation task with respect to time at high levels of interaction.

In terms of gender differences, there was no significant difference between genders in accuracy in either auditory task. However, in the arithmetic task, women took more time than men at a high level of physical activity versus medium and high mental loads. In addition, women had higher HR and MBP than men in the arithmetic task at high levels of workload interaction.

The physiological variables were significantly impacted by mental workload and physical activity interactions. Heart rate, heart rate variability, and mean blood pressure were sensitive to both physical and mental workload demand in both the arithmetic and tone localisation experiments. The results of this chapter indicate that rSO2 was a valuable objective that reflected the impact of physical and mental workload combinations on attentional resources through measuring oxygenation changes in the brain. It was sensitive to physical and mental workload difficulty changes. Moreover, the NIRS technology is a valuable technique for reflecting mental workload with respect to cognitive capacity and brain activity.

The subjective assessment of the NASA-TLX overall score was sensitive to physical and mental demand changes. The important issue was that physical workload level changes did not affect participants’ mental workload perception since the impact of physical workload on the mental demand dimension was not significant; the impact of mental workload on the physical subscale was also not significant. However, according to the overall TLX score, the TLX increased significantly as the physical and mental workloads increased, so it seems that the TLX is a valuable subjective measure of the overall workload. The Borg-CR10 and RPE were affected by physical load difficulty but were not impacted by the levels of mental load.

Thus, in this chapter, there was a significant effect of physical lifting and mental workloads on auditory resources in Wicken’s model (1984) and performance. Low and medium physical lifting workloads led to better performance (i.e., accuracy and time of task) at a low and medium auditory mental workload, similar to the Chapter 4 and 5 findings, which explained the contributions of low and moderate physical activity levels during visual and auditory task performance. Then, the importance of different physical activities’ contributions to visual and auditory information processing under controlled conditions (laboratory conditions) was found. In Chapter 7, a field study was conducted to validate and examine the results of laboratory experiments through an examination of the impact of physical and mental workload interactions in a product assembly job.

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CHAPTER 7:

THE EFFECTS OF ASSEMBLY TASK WORKLOAD ON PERFORMANCE: A CASE STUDY OF ASSEMBLING MERCEDES TRUCKS IN SAUDI ARABIA

7.1 INTRODUCTION

As noted in Chapter 3 (see section 3.4), the current chapter validates and translates the results derived from laboratory experiments into a field setting. So far, after investigating the impact of physical and mental workload combinations on visual (arithmetic and spatial figures) and auditory (arithmetic and tone localisation) tasks in a laboratory setting (Chapters 4, 5 and 6), the research has demonstrated these headline findings: first, that low physical workload leads to better performance (accuracy and time of task) in visual and auditory tasks at low mental demand. Also, low physical load (20% of Wmax) leads to better performance in visual tasks at a medium level, and time of task in auditory tasks at the same level. Second, a medium physical workload (50% of Wmax) leads to better task time in both visual tasks at a medium load but not the best as was hypothesised. Third, the participants' performed better at the medium physical workload and low mental workload interactions in visual and auditory tasks. This result may have occurred because the increasing level of physical activity led to increased physiological arousal, thus the better performance occurred. Moreover, the previous chapters (4, 5 and 6) found that physical activity reduced brain activation by supplying more oxygen to the brain, which helped create a balance between the oxygen available in the brain and the amount of oxygen needed to meet the mental workload, so better performance occurred. Fourth, high (overload) physical load led to the worst performances at a high (overload) mental demand level in visual and auditory tasks. This is because the overload interactions led to increased arousal and the effect of physical activity on oxygenation changes in the brain was not significant at high levels of workload interaction. The thesis now aims to translate these laboratory results into a field sitting to examine the impact of assembly job workload on performance in truck assembly. Before that, the background for the assembly field study and workload will be discussed.

Many jobs in the real world require meeting both physical and mental demands. For example, military, firefighting, driving and industrial jobs require such workload interactions (Perry et al., 2008). In particular, assembling products is a common task in the industrial field (Stoessel et al., 2008). According to Stork and Schubo (2010), assembly production line jobs require mental and physical activity. In addition, in order to lift parts during the assembly process and to handle materials, operators must use mental functions that include monitoring, perception, attention and memory to complete the assembly tasks. In addition, the operator must use his/her cognitive functions in this type of task; perception is needed to recognise the stimulus and extraction characteristics (Stork and Schubo, 2010). Assembly work is very complex because it includes a number of variables to identify the difficulty of a task. In other words, the task includes many variables that need to be considered, such as the weight and size of assembly parts, the steps or instructions of the task and the time needed for the task (Stork and Schubo, 2010). Manual assembly production lines impose a physical and a mental workload to lift materials and attach them in the correct position; all of these processes impose a physical demand on the operators (Tang et al., 2003). So, that means the physical activity in an assembly job can impact positively or negatively on operators' cognitive information processes, which may facilitate or impair performance. Additionally, the various allocations of visual attention and recalling information about the assembly steps from memory, concurrent with physical activities, could lead to mental bottlenecks (Stork et al., 2008). Therefore, an increase in physical and mental workload interaction could increase errors and time taken to complete the tasks.

Indeed, task workload in assembly lines depends on the types of models and products (Stoessel et al., 2008). For example, Zaeh et al. (2009) mentioned that assembly work requires an operator to pay close attention in attaching each part in the correct place; moreover, physical movement is required to lift the parts. They said large increases in the size of assembly parts negatively impacts on the assembly process through the impact on cognitive information processing. These requirements make these jobs especially demanding. However, assembly tasks may include various cognitive loads, such as perception, attention and concentration, in addition to physical movements and carrying parts and tools required to complete the task under time constraints. Moreover, an excessive workload (i.e. mental and physical demand) can generate stress and fatigue. Balancing between operating system demands and individual capacity is important to increase productivity and reduce errors (De Zwart et al., 1995; Stork et al., 2008). Therefore, if the assembly system is not well designed, the possibility of overload from physical workload and information processing required during product assembly tasks, compounded by environmental factors (e.g. temperature, noise and humidity) may lead to poor quality final products and an increase in errors (Stork and Schubo, 2010).

According to De Zwart et al. (1995), the designer should consider workplace design and create a balance between task workload, human physical capacity and mental limitations, to improve performance and save time. In addition, these authors claim that proper workplace design reduces management costs and operator injuries. Therefore, studying the effect of workload interaction in assembly tasks under different levels of workload on operator performance is important in determining the correct balance between operators' physical and mental capacities and the demands of assembly tasks. Such a balance can support management with valuable recommendations for design of the workplace.

This chapter also aims to validate the results derived from previous chapters' experimental findings (Chapters 4, 5 and 6) through translating the laboratory findings to a field setting in a Mercedes truck assembly factory. However, controlling the other environmental factors in the field situation was difficult. A visual task was selected over auditory tasks because setting the test conditions in real-world jobs instead of in laboratories is problematic. This task was selected because truck assembly lines include different levels of visual and mental demands related to the number of sub-components that need to be gathered to complete the process. In addition, the operators must lift various parts that are of different sizes. This approach would increase the ability of designers to manage workload levels (i.e. balancing the assembly workload and operators' attentional limitations) as part of a proactive approach by the factory to reduce injuries and improve performance through optimum effort.

7.2 METHOD

7.2.1 Design

The current study investigated the impact of physical and mental workloads imposed by three different selected parts of assembly tasks in the Mercedes truck assembly line (side mirrors, front bumper, and side doors, as marked in Figure 7.1.) The selection of these items was based on the weight, size, and number of sub-component parts for each assembly item task. The weight and size were chosen as criteria to reflect physical workload; the side mirrors were selected to reflect the low physical lifting workload. The front bumper was designated as the medium physical level because two workers lift the bumper manually. The side doors were identified as the high physical lifting workload because one operator lifts the door.

The three selected assembly items were allocated to three different levels of mental workload. These levels of mental demand depended upon the number of sub-components as a condition of mental visual-spatial monitoring difficulties. For example, the operator must fulfil four sub-component tasks to complete fixing the mirror, whereas the operator must complete six sub-tasks to finish the bumper assembly. In the door condition, the operator needs to complete eight sub-tasks to assemble the door. Table 7.1 illustrates the three different parts that were selected; the table also explains the physical demand and mental workload for each assembly item. In addition, Table 7.2 presents the interaction workload levels for the three parts depending upon the level of visual mental workload and physical lifting load.

The table includes the sub-components for each item, standard time to complete the item task, and total number of completed parts per day. The operators work eight hours per day, and the day is divided into three different types of work. For example, the operator who works on the side door assembly task must complete 28 doors per day because he has another task he needs to complete. The factory aims to complete 14 trucks per day. Time constraints also apply to the front bumper item and the side mirrors item; the operators need to complete 23 bumpers and 40 mirrors per day. Throughout the day the operators are not only working on these items; they have other tasks they must do.

Figure 7.1 Photograph of Mercedes truck showing the three parts that were evaluated in this study

Table 7.1 Descriptions of physical and mental workload, standard time, and number of assembled parts per day for the three different assembly parts for Mercedes trucks

Parts Name	Physical Load	Mental Load	No. of Sub-component Parts	Standard Time min/part	Total number of completed parts/day
1- Side Doors	Lifting the door manually and putting in the correct position. Holding it in position until fixed.	The operator is required to screw in seven screws.	8 sub-tasks, 7 screw tasks and one in mounting and balancing the door.	12	28
2- Front Bumper	Lifting the item and keeping it supported until fixed.	The visual tasks are to complete six screws and assemble the part.	6 sub-tasks, mounting and six bolts of screws.	10	23
3- Side Mirrors	Manually lifting the mirrors and keeping them supported until fixed.	Attention and visual tasks to fix 4 screws and assemble the part.	4 sub-tasks, 4 screws	2.5	40

Table 7.2 The three conditions of interaction of physical load and mental workload

		Mental Visual Workload		
		Low visual spatial load	**Medium visual spatial load**	**High visual spatial load**
Physical Lifting Parts	**Low lifting load**	MIRROR ASSEMBLY	×	×
	Medium lifting load	×	BUMPER ASSEMBLY	×
	High lifting load	×	×	DOOR ASSEMBLY

7.2.2 Hypotheses of the Study

As stated previously in section 7.1, according to laboratory experiments, the better accuracy in visual and auditory tasks was observed at the low physical level × low mental workload. In addition, the medium physical workload led to better task time in visual tasks at the medium mental workload and there were no differences between task time at low and medium visual workloads under a medium physical level (see Chapter 4 and section 7.1), since an increasing level of physical activity led to an increase in physiological arousal level, which led to better performance. This was consistent with previous research, which concluded that incremental increases in physical activity lead to a rise in arousal level, so cognitive visual and auditory information processes are facilitated (Audiffren et al., 2009; Mozrall and Drury, 1996). Furthermore, accuracy in both auditory tasks at low mental workload was better at the low physical workload, since there were no significant differences between accuracy at these levels of workload interaction. In contrast, task time in auditory tasks was better at the low physical level × low or medium mental workload, as was shown in Chapters 5 (also see previous section 7.1).

- *The better accuracy will occur at a low physical load × low visual mental workload (mirrors assembly).*

- *The better time of task will occur at a medium physical load × medium visual mental workload (bumper assembly) as well as at a low physical load × low visual mental workload (mirrors assembly)*

According to the results in Chapters 4, 5 and 6, participants' worst performance occurred significantly with high levels of physical and visual mental workload interaction in both visual mental tasks (verbal arithmetic task and spatial figures task) as mentioned previously in section 7.1. In addition, the participants' worst performance appeared with high levels of physical activity (cycling and lifting tasks) and auditory mental workloads. That may be because of the increasing level of physiological arousal due to high workload. In addition, according to Stork and Schubo (2010), overload on the assembly task due to increasing size and weight of the parts to be assembled and the complexity level (requiring increased concentration) leads to a large amount of errors and worse performance. Therefore, the hypothesis for this experiment is as follows:

- *The worst performance will occur at a high lifting load × high visual mental load (door assembly) due to overload workload interactions and a high level of physiological arousal.*

7.2.3 Independent and Dependent Variables

The current study included two independent variables: physical workload with three levels of difficulty and mental workload with three levels of complexity, as mentioned previously (see section 7.2.1). There were three dependent variables: first, the performance measure, which included accuracy which was calculated according to the proportion of components successfully installed in each assembled part, as illustrated in Table 7.1 and task completion time. The second variable was heart rate (HR) as a physiological indicator. The other physiological measures were difficult to record in this study because it was carried out in the field. Third, the subjective assessment tools included NASA-TLX scores to measure the task workload (Hart and Staveland, 1988). In addition, the NASA-TLX is reliable to implement in the real domain to reflect multi-task workload (Dorrian et al., 2009); the NASA-TLX measure used was the total unweighted workload. Furthermore, as shown in previous chapters, an analysis of the mental demand dimension (MD) and physical demand dimension (PD) in the TLX score was carried out, as the purpose of this thesis is to determine the impact of physical demands on mental subjective assessment tools and individual perception while performing cognitive tasks.

7.2.4 Assembly Tasks

The experiment included three assembly tasks, as mentioned previously in section 7.2.1. Table 7.1 illustrated the descriptions of each part including the standard time taken to assemble each part, number of sub-components for each part, and number of completed parts per day. The workers in each task must lift the parts and attach them in the correct position (usually in two steps); these steps include picking up the part, putting it in the correct position, and fixing it. First, in the doors assembly task the operator must lift the door manually and put it in the right position; he must then support the door until he fixes the screws. There are four screws in the top hinges and three screws in the bottom hinges of the door. The door balancing process is the last sub-task. In the bumper assembly, the operator must lift the bumper with another worker and position it in the correct way; then he continues to support the bumper and affixes the four screws in the middle. Then he attaches two screws on each side of the bumper. The mirrors task includes two steps. In the first step, the operator must carry the mirror and position it correctly while supporting it in one hand. Then he needs to attach four screws. The figures below illustrate the three parts that were used in this study. Figures 7.2a and 7.2b are schematic diagrams showing the number of screws that are required to fix each part.

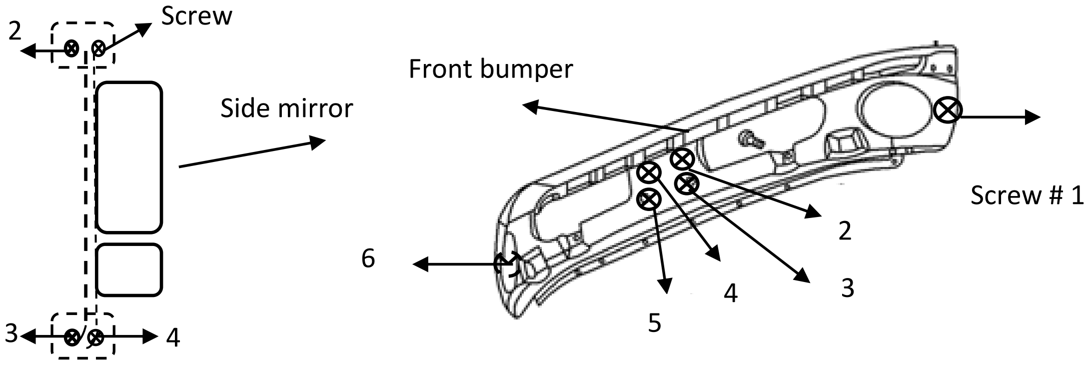

Figure 7.2a The schematic diagram of side mirror and front bumper and number of screws that are required to fix them in place

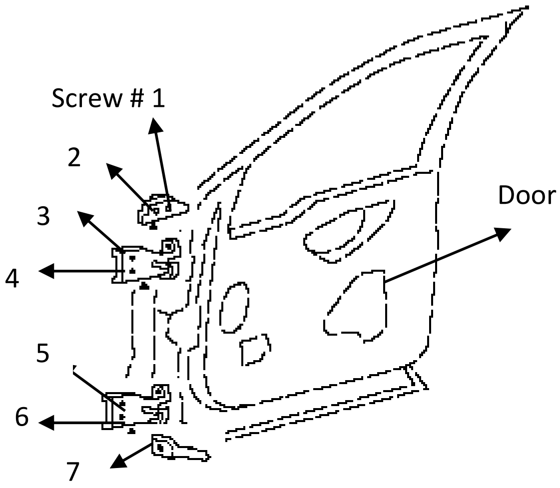

Figure 7.2b Side schematic diagram view of door and number of screws that are required to fix it

7.2.5 Participants

Fifteen skilled male workers (aged 25–35) participated in this study. Table 7.3 illustrates the descriptive statistics of the group that performed each assembly task.

Table 7.3 Descriptive statistics of participants for each assembly part (mean ± SD)

Assembly Part	N	Age	Height (cm)	Weight(kg)	HR-rest (beats/min)
Side Doors	5	28.2±2.3	172.3±4.5	77.4±7	71.7±5.9
Front Bumper	5	31±3.9	171.8±5.2	75.1±5.4	75.2±4.3
Side Mirrors	5	30.6±2.9	174.0±4.1	78.7±6.4	72.9±3.2

7.2.6 Procedure

To avoid repetition, the procedure follows the description presented in Chapter 3 (see section 3.4.6).

7.3 RESULTS

The results are divided into three main sections. The first section is the performance analysis, which includes the accuracy and time for each task. Second, heart rate was measured. Finally, the assessment of subjective variables was made through NASA-TLX and Borg's CR10 and RPE scores.

7.3.1 Performance

Accuracy and Time of Task

A Kruskal-Wallis analysis showed no significant impact on participants' accuracy for assembly task workloads (physical and mental workloads) ($p=0.116$).

On the other hand, the Kruskal-Wallis test showed that the assembly workloads significantly affected task time ($p<0.05$). The time taken to complete each task increased significantly as the workload of the assembly task increased. According to a Mann-Whitney test there was a significant difference between the time for the mirror assembly task versus that of the bumper task and time for the bumper assembly task versus the door assembly task ($p<0.05$ for both) (Figure 7.3).

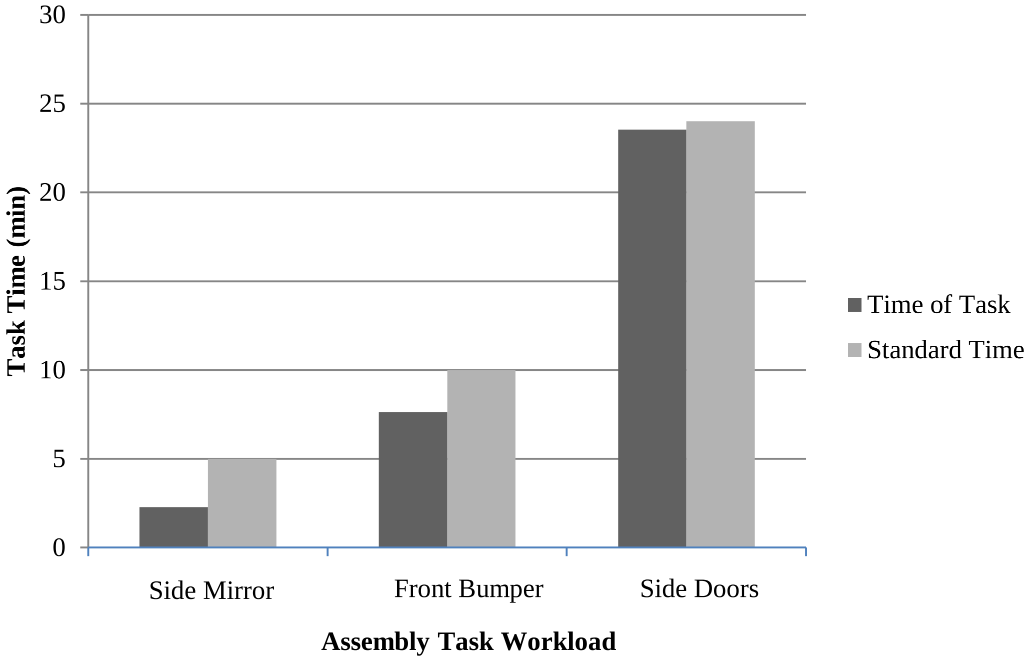

Figure 7.3 Three parts of assembly products actual time and standard time

In terms of comparison between the actual time of task and the standard time (theoretical value was obtained from the factory data recording) the One Sample Wilcoxon (signed-rank) test was used. The standard time to affix two mirrors is 5 min, whereas the average actual time of five participants was 2.28 min to complete assembly of two mirrors; there was a significant difference between actual mirror placement time and standard time ($p<0.05$). In addition, the standard time of bumper assembly (medium assembly workload) is 10 min and the average time of five participants in this assembly task was 7.63 min; the difference between actual time and standard time was significant (p<0.05). In contrast, the standard time of both side doors is 24 min and the average time of five participants in this assembly task was 23.74 min; there was no significant difference between the task completion time and standard time for doors assembly (p=0.173) (Figure 7.3).

7.3.2 Heart Rate

Heart rate was measured as a physiological indicator to reflect the stress of these tasks on changes in the physiological state of the participants during the assembly task's duration. The Kruskal-Wallis test analysis showed a significant impact on participants' HRs relating to physical and mental workload during assembly (p<0.01). In addition, increasing levels of assembly task workloads led to an increase in HR (Figure 7.4).

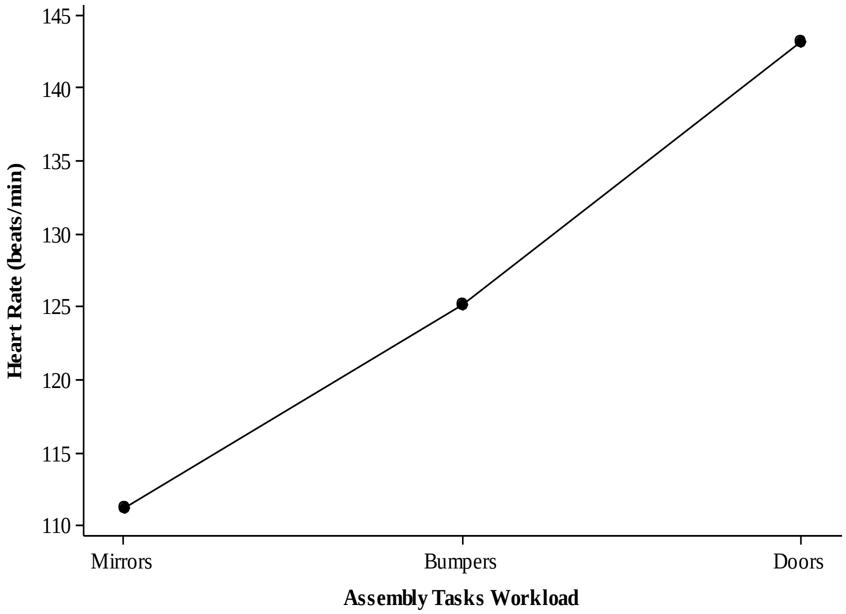

Figure 7.4 Heart rate against the assembly tasks workload

According to the Mann-Whitney test there was a significant difference between HR in the side mirror vs. bumper task (p<0.01) and bumper task vs. side doors task (p<0.01).

7.3.3 Subjective Assessment Tools

The subjective assessment technique included three rating scores. NASA-TLX was used to determine the mental workload of each assembly task. In contrast, Borg's scores CR10 and RPE were used to evaluate the physical workload of each assembly task.

NASA-TLX Assessment Tool

First, the calibration process of NASA-TLX was carried out based on an arithmetic task as stated in the study procedure in Chapter 3 (section 3.3.5). Each group of operators was asked to complete three different levels of arithmetic (low, medium and high); the selection of the levels was randomised and then TLX scored for mental workload for each assembly task. In the case of the mirror task, the Mann-Whitney test showed that there were no significant differences between the low arithmetic task and mental mirror assembly load (p=0.143), whereas there were significant differences between mirror workload vs. medium arithmetic load and mirror load vs. high arithmetic task (p<0.05) (see Figure 7.5). In addition, the analysis found no significant difference between the medium arithmetic task and the mental bumper assembly load (p=0.35), whereas there were significant differences between bumper workload vs. low arithmetic load and bumper load vs. high arithmetic task (p<0.05) (see Figure 7.5). In the door assembly task, the analysis showed that there was no significant difference between the high arithmetic task and mental door assembly load (p=0.54), whereas, there were significant differences between door workload vs. medium arithmetic load and door load vs. low arithmetic task (p<0.05) (see Figure 7.5). The Kruskal-Wallis test showed that the effect of mental workload of assembly tasks on the NASA-TLX mental demand dimension was highly sensitive to mental workload levels (p<0.01).

In addition, the task workload impacted the NASA-TLX as expected; with increasing workload the scores increased (p<0.01) (Figure 7.5). Participants scored the highest rating for the door assembly task, whereas the lowest score was observed in the mirror assembly task. A Mann-Whitney test showed a significant difference between the mirrors task × bumper task, and bumper task × doors task; overall TLX score (p<0.01 for both).

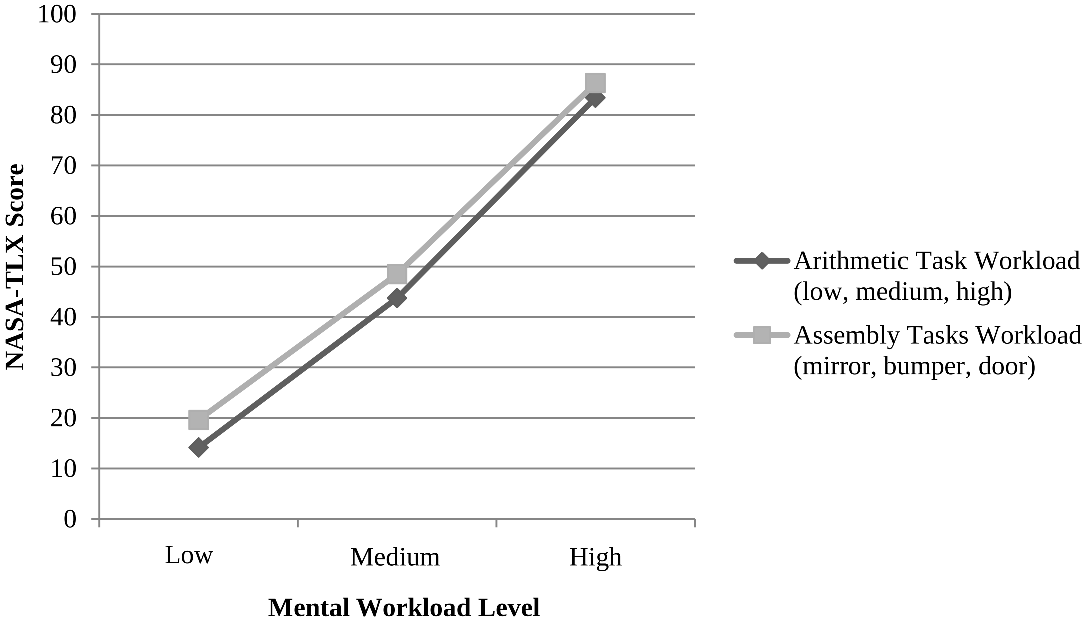

Figure 7.5 Mean NASA-TLX score of arithmetic task levels against the three levels of assembly tasks

In this section the effect of assembly task workload on MD and PD in TLX is presented. As mentioned previously in section 7.2.3, the purpose of this thesis in terms of theoretical development is to see whether the subjective metric tool (TLX score) can be effectively used to show the impact of physical activity changes on MD and the effect of mental workload changes on PD. The result of the effects of physical assembly levels on MD appears significant. Moreover, the impact of mental workload levels on PD also seems significant. In this real world scenario, the number of physical and mental workload interactions was constrained to three levels since it was difficult to set up nine conditions in the field study, as there were in the laboratory-based studies.

In terms of MD, the Kruskal-Wallis test showed that the changes of physical workload levels in the three assembly tasks had a significant impact on MD ($p<0.05$). In addition, according to a Mann-Whitney test, there were significant differences between the MD score in the mirror assembly task versus the bumper assembly task ($p<0.05$) and the bumper task versus the door assembly task ($p<0.05$) (see Table 7.4).

In terms of physical workload, the Kruskal-Wallis test indicated that the changes of mental workload levels in the three assembly tasks had a significant impact on PD

($p<0.05$). In addition, according to the Mann-Whiney test there were significant differences between the PD score in the mirror assembly task versus the bumper assembly task ($p<0.05$) and the bumper task versus the door assembly task ($p<0.05$) (see Table 7.4).

Table 7.4 Average MD and PD in NASA-TLX rating for three assembly tasks

	Mirror assembly task	Bumper assembly task	Door assembly task
MD	7	43	74
PD	11	48	83

Borg's Scales CR10 and RPE

The calibration process of Borg's scales was carried out based on the cycling task. Each group of operators was asked to complete three different levels of cycling (20, 50 and 80 % of Wmax). The level was selected randomly and then compared with the Borg-CR10 and Borg-RPE score for the mental workload of each assembly task. In terms of the CR10 score, in the mirror task the Mann-Whitney test showed that there were no significant differences between the low cycling task and the lifting mirror assembly load ($p=0.24$), whereas there were significant differences between the mirror physical workload vs. medium and high cycling load ($p<0.05$). In addition, the analysis found that there were no significant differences between the medium physical level (50% of Wmax) and bumper physical assembly load ($p=0.093$), whereas there were significant differences between bumper physical load vs. low and high cycling load ($p<0.05$). In the door assembly task, the analysis indicated that there were no significant differences between high physical load (80% of Wmax) and door assembly physical load ($p=0.074$), whereas there were significant differences between door workload vs. medium and low cycling load ($p<0.05$) (see Figure 7.6 for CR10 score).

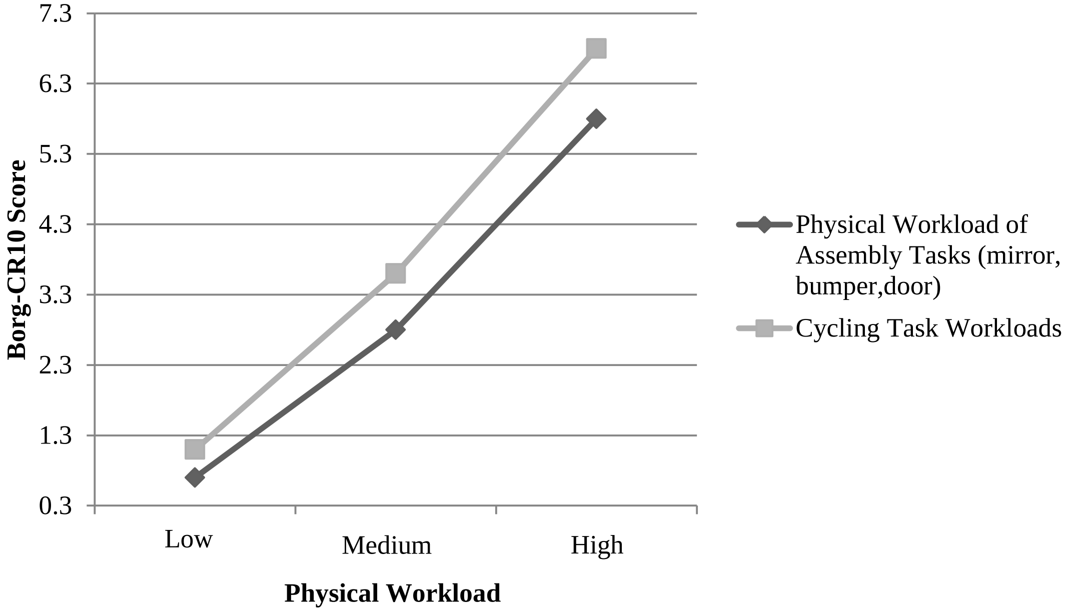

Figure 7.6 Mean Borg-CR10 score of cycling task levels against assembly tasks for the three assembly levels: mirror, bumper and door respectively

In terms of the Borg-RPE score, in the case of the mirror task, the Mann-Whitney test showed that there were no significant differences between the low cycling task and the lifting mirror assembly load (*p*=0.102), whereas there were significant differences between the mirror physical workload vs. medium and high cycling load (*p*<0.05). In addition, the analysis showed that there were no significant differences between medium physical level (50% of Wmax) and bumper physical assembly load (*p*=0.34), whereas there were significant differences between bumper physical load vs. low and high cycling load (*p*<0.05). In the door assembly task, the analysis showed that there were no significant differences between high physical load (80% of Wmax) and door physical load (*p*=0.083), whereas there were significant differences between door workload vs. medium and low cycling load (*p*<0.05) (see Figure 7.7 for RPE score).

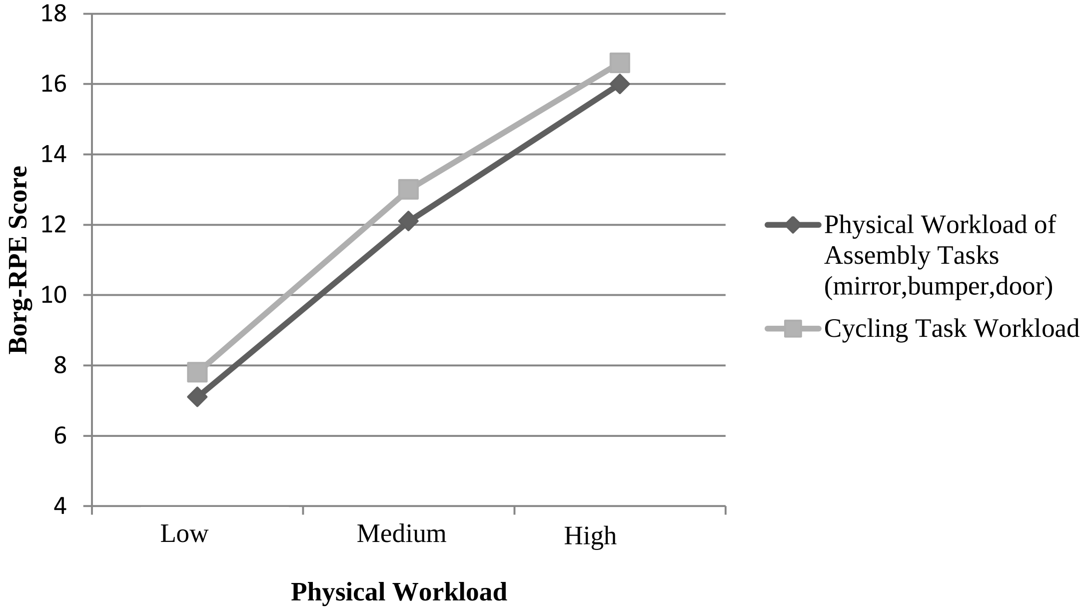

Figure 7.7 Mean Borg-RPE score for cycling task levels against assembly task levels: mirror, bumper and door respectively

As expected, the Borg CR10 and RPE were sensitive to physical workload of assembly tasks ($p<0.01$ for both). Increasing CR10 and RPE scores were associated with increasing levels of assembly task physical workloads. For example, the highest Borg-CR10 and Borg-RPE occurred under the door assembly task, whereas the lowest scores were observed under the mirrors task. However, the Mann-Whitney test indicated a significant difference in Borg-CR10 scores between the physical workload levels in the mirror vs. bumper task ($p<0.05$) and the bumper task vs. the door assembly task ($p<0.05$) (see Figure 7.8). In addition, there were significant differences in Borg-RPE scores between the mirror vs. bumper task ($p<0.05$) and the bumper task vs. doors assembly task ($p<0.05$) (see Figure 7.8).

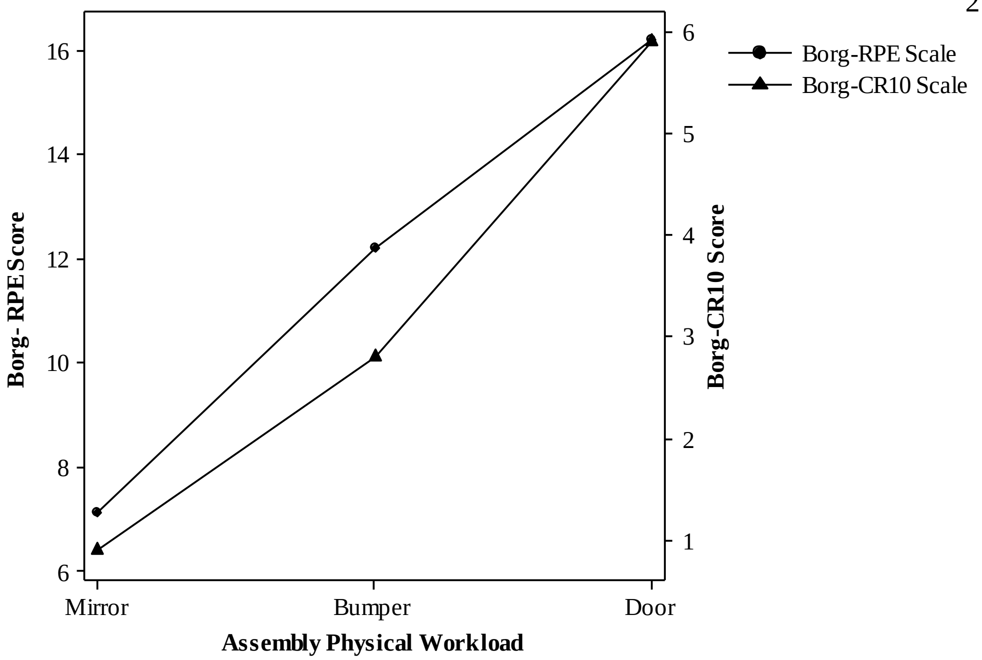

Figure 7.8 Mean Borg-CR10 and RPE scores against the three physical workload assembly tasks

7.4 DISCUSSION

This study was conducted to validate the experimental results of Chapters 4 and 5. It was implemented to translate the experimental setting into a field setting, to evaluate the effect of physical and mental workload interactions of assembly items on operators' visual performance. Thus, it will be useful to determine the range of consistency between the results of the laboratory and field setting experiments. The present study evaluated the effects of assembly tasks for three parts in a truck assembly production line: side mirrors, bumpers and side doors.

The results of this study showed that the performance accuracy of operators in three assembly task conditions did not change significantly during these tasks. That means the interaction between physical and mental workload did not affect accuracy. That probably means the performance of workers on these was at ceiling. That may be because all the operators were experts, which reduces the effect of the workload factor on accuracy; therefore accuracy was constant among the three assembly conditions. However, this result was not consistent with the results from Chapters 4 and 5 which indicated that participants' accuracy was affected by the physical and mental workload interactions in visual and auditory tasks. In addition, this field study illustrated that accuracy was not affected by overload workload conditions (i.e., door assembly); whereas the previous chapters found that the overload workload leads to worst performance in the accuracy of visual and auditory tasks attributable to an increased level of physiological arousal. According to Stork and Schubo (2010), a high level of skill reduces the impact of mental demand and errors made by individuals in assembly process tasks. More importantly, the field study was constrained by the number of workload combinations, unlike the experimental setting, so that may have had an impact on the results.

On the other hand, the task time metric used in this field study verified the three different levels of mental and physical workload interactions (assembly tasks), since this study illustrated that increasing physical and mental demands influenced the assembly time tasks tested in this experiment. That means the three different assembly task workloads that were assumed in this study were verified. The time taken to carry out the task was significantly increased as the assembly task workload increased. The door assembly task had the longest mean time, whereas the mirror assembly task had the shortest.

In addition, the pattern of time results in this study was consistent with the pattern of the time in experimental studies. The actual average time for operators to complete the two side mirrors was 2.28 min, whereas the standard time for assembly of two mirrors was 5 min. The results showed that the actual time was lower than the standard time, meaning that the time at the low physical workload was better than the time at low mental workload. In addition, the actual average time for the bumper assembly task was lower (7.63 min) than the standard time of the task (10 min). This may be because the incremental increase in physical activity led to an increase in the physiological arousal, which led to better cognitive information processing at a medium mental load. In contrast, the average time for the operators to complete the two side doors assembly task was 23.74 min whereas the standard time was 24 min, indicating that there was no significant difference between the average of the actual time and the standard time. Therefore, the overload of workload in the assembly of side doors consumed approximately all the standard time, whereas the other assembly parts (side mirrors and bumper) consumed less time than allotted by the factory. Thus, the most important findings are that the time pattern in the field study was consistent with the time pattern in the laboratory experimental results, since this result was similar to the findings in Chapters 4, 5 and 6, which concluded that low physical workload leads to better time of task in visual and auditory tasks at low mental demand. In addition, medium physical workload leads to better time of task in visual tasks (arithmetic and spatial figures tasks). Finally, the overload of physical and mental workload interactions leads to worst task completion times in visual and auditory tasks. According to Stork and Schubo (2010), the assembly process with high physical load (i.e., size of the parts) and high cognitive requirements could increase the number of mistakes and time needed to complete the task. In addition, the increasing number and size of sub-components required for assembly negatively influenced operator performance. For example, Zaeh et al. (2009) pointed out that an increase in assembly parts in one item caused a decrease in hand movement velocity and more errors. According to Wickens and Hollands (2000), time pressure can increase the level of arousal stress, which may influence the information received through visual input, thus decreasing performance. However, the worst performance may be affected by fatigue from an overload of work and environmental stresses in a factory. Moreover, HR increased significantly as the assembly workload increased from mirror to bumper assembly. This finding was consistent with those of previous researchers, who found that a medium level of physical exercise leads to improvement in the visual information process by increasing the level of arousal, shown by a curved line to represent the relationship between arousal and performance (Antunes et al., 2006; Audiffren et al., 2008; Mozrall and Drury, 1996).

This chapter argues that the task time metric was verified by the three assembly workloads that are assumed in the field study. That means the experimental manipulation was successful in achieving three different workload interaction conditions in this study. Thus, the task time variable was validated by the three levels and obtained similar patterns of task time in an experimental setting, so it was a valid variable to use in the field study.

More interestingly, HR data verified the three assembly physical and mental workload interaction conditions that were assumed in this study. HR increased with mental and physical workload in the assembly task. The highest average HR was observed at the high assembly task workload (i.e., side door assembly). The average HR of participants was highest with high physical and mental workload interactions (i.e., side door assembly), which may be due to the increasing level of physical and mental workloads in this assembly task, because the operators must fix seven screws and execute the door balancing process during the door assembly task beside the heavy weight of the doors. In contrast, mean heart rate decreased under medium physical load with medium mental demand for the bumper task. For the bumper, the operator must lift the bumper and fix six screw tasks at the same time. The lowest mean HR was observed under low physical load with low mental demand (mirror assembly). This result pattern was consistent with the experimental studies, which showed HR increasing with increased physical and mental workload combinations, as arousal level was increased. So the experimental manipulation succeeded.

HR was sensitive to changes in the physical and mental workload assembly tasks, since it increased significantly when the task changed from side mirrors to bumper and to side doors. These results are consistent with the experimental studies in Chapters 4, 5 and 6, showing that HR is sensitive to mental and physical workload changes in visual and auditory tasks. All of these results were in agreement with Li et al. (2009), who found that heart rate frequencies significantly increased, as the level of manual material handling difficulty (e.g. size of the box, weight of box and number of lift frequencies) increased. The increasing HR value was associated with rising physical and mental workload difficulties (Audiffren et al., 2009; Fredericks et al., 2005). Finally, because the study was conducted in the field, environmental stressors (e.g., heat and noise in the factory may have influenced heart rate, and this should be considered because the temperature ranged from 30 °C to 35 °C during the day shift. Noise and external heat factors can increase the level of physiological arousal and physiology changes, such as increasing heart rates (Wickens and Holland, 2000). This chapter finds that HR is a valid measure to use in a field study.

In terms of overall TLX scores, the results showed that the TLX rating verified the three levels of physical and mental workload interactions assumed in this assembly task, since the lowest TLX scale appeared under a low physical load with low mental assembly workload (mirror assembly); it was increased under medium physical and mental assembly load combinations (bumper assembly), and was highest at overload workload interactions (door assembly). This pattern in TLX score results was similar to the experimental studies in Chapters 4, 5 and 6. However, the scale was sensitive to changes in the physical and mental workload interactions of the three assembly tasks. The results of this study were consistent with a previous assembly study that confirmed that increasing complexity of assembly leads to increasing overall NASA-TLX scores (Tang et al., 2003). The laboratory results also showed that the NASA-TLX was sensitive to variations in the visual and auditory mental task workload and was affected by increasing difficulties in physical cycling and lifting demands. Thus, the multi-dimensional rating technique (NASA-TLX) is valuable in detecting and evaluating the overall workload that includes concurrent physical and mental task demands (Hart and Staveland, 1988).

In terms of the mental and physical demand dimensions on NASA-TLX scores, the results showed that the dimension was sensitive to changes in the mental workload of the three assembly tasks because a high score on the mental subscale was associated with complex mental workload. For example, participants scored higher on the doors assembly task than the bumper assembly task. The score for the mirror assembly task was lower than for the bumper assembly task. However, the results of this study were consistent with the previous experiment studies (Chapters 4, 5 and 6) that confirmed that an increasing level of mental task workloads leads to increased overall NASA-TLX scores. This result was similar to results in a previous paper that found that the TLX score was sensitive to changes in the difficulty level of the visual workload (e.g. Hwang et al., 2008). However, the effect of physical workload on the mental demand dimension was significant because the field study was constrained to three levels, so if there were more than three levels of workload interactions, the effect of physical workload may not have been significant. In addition, the impact of mental workloads on PD was significant.

However, the perceived physical workload assessments from the Borg-CR10 and Borg-RPE justified the three physical workloads assumed in this study. In the door assembly task, high physical load scores were observed, whereas a lower score was recorded for the bumper task and the lowest for the mirror assembly task, indicating that the latter two needed lower physical capacity than the door assembly task. These assessment tools are commonly used to evaluate physical demand level; the sensitivity of the scale in this study supported previous results that ratings increased with additional physical demands (e.g. Borg et al., 1987; Borg et al., 1998; DiDomenico and Nussbaum, 2008). According to Hattori et al. (2000), the CR10 and the perceived exertion (RPE) scores increased remarkably when the lifting weight increased from 10 kg to15 kg. However, the current results were also consistent with the previous experimental studies in Chapters 4 and 5, which found that increasing physical workload from 20% to 50% of maximum workload capacity when cycling was significant. In addition, the results presented in Chapter 6 showed increasing levels of box weights from 8% to 14% to 20% of body mass led to an increase in the RPE and CR10 scores. That means the translation of an experimental setting into a field setting was confirmed, since the three different levels of mental and physical loads in this study were satisfied and the results pattern was similar to experimental study findings.

7.5 CONCLUSION

With multitask workload, such as assembly tasks, balancing individual attentional resource limitations and the task workload is necessary to achieve the best performance level and increase productivity. Some level of physical activity workloads could lead to better performance of cognitive tasks. Generally, the translation setting from experimental conditions into field setting succeeded, since the pattern of results of task time, HR, overall NASA-TLX scale and Borg's scales in this study were consistent with the experimental manipulation and setting. In addition, the different levels of physical and mental assembly workloads (mirrors, bumper and doors) assumed in this study were verified by these measures. However, the accuracy of the three assembly tasks was not significantly affected by the workloads because no differences in the accuracy of the tasks were found. Such a result may relate to the experience and skill of the operators.

However, the low physical workload for the mirror assembly task led to better actual time of task assembly. Furthermore, the result showed that the moderate level of physical activity for the bumper assembly task also led to better actual time for this task because the standard time for both the mirror assembly task and the bumper task was higher than the actual time. This may be because physical activity leads to an increase in arousal level, thus improving the attention and cognitive visual information processing of the operators. These results were supported by the experimental study presented in Chapter 4, which showed that the better time of task occurred at the moderate level of physical exercise × medium mental workload in visual tasks. In addition, the time needed for visual and auditory tasks was better at the low physical level × low mental workload.

As expected, the overload in assembly workload (i.e., the door assembly task) led to worst task completion times because there was no significant difference between the standard time allotted by factory management and the actual time of the task. This lack of a difference may result from the highly increased level of arousal from high workloads in addition to environmental factors (e.g., temperature) because the highest HR value was observed during the door assembly task and it was nearly the same as the HR value at a high level of physical workload in the cycling condition (80% Wmax). The number of sub-components of assembly increased in addition to the heavy weight of the parts. Therefore, pressure on attentional capacity and physical capacity was increased as a result of the overload.

Previously, the objective heart rate measure has been used to reflect workload in dual task situations. In this study, HR reflected that increasing levels of assembly workload interactions affected the physiological state of participants. In term of the three levels of difficulty of the assembly tasks (mirror, bumper and door tasks), the assumption of this study was validated and justified, since heart rate significantly increased between these three assembly tasks. The lowest mean HR value was observed under the mirror assembly task; the moderate HR value appeared during the bumper assembly task, and the highest HR occurred during the door assembly task. HR was verified and justified the three levels of physical and mental workload (assembly workload) that are assumed in this study.

Overall, the subjective assessment tool, NASA-TLX, justified the three levels of physical and mental workloads proposed in this study, because the mirror task had the lowest TLX score, whereas the door assembly task was observed to have the highest.

Borg's CR10 and RPE scores also verified the three physical lifting loads that were assumed in this study, since the Borg scores presented significant differences between the physical load of the mirrors, bumper and door assembly tasks. These subjective and objective measurements were beneficial to reflect simultaneously the physical and mental workload in the real domain.

Generally, these results were consistent with previous laboratory experiments explained in the research chapters that showed that multitask performance was influenced by the level of physical and mental demands. In addition, the results of this study contribute to workplace design by leading to operator better performance and reducing injuries and costs by redesigning task procedures and task systems to balance the level of physical and mental workload, operators' attentional limitations and physical capacity in a dual-task paradigm. Designers can mitigate overload by using technology such as an automation system for assembly tasks with high workload interactions that require extensive physical activity, in order to achieve a balance between task workload and physical capacity (De Zwart et al., 1995). They could, for example, use a movable conveyor that could load the door part, so, the physical load on the operator could be reduced, leading to a time saving. In addition, the mental workload could be reduced by implementing an automation system (such as robot technology) to fix the complex sub-component parts which would reduce time and errors (Stork and Schubo, 2010).

CHAPTER 8: DISCUSSION AND CONCLUSION

8

8.1 INTRODUCTION

This chapter presents the integrated results of the experimental studies and field study. The aim of this PhD thesis was to understand the effects of different levels of physical and mental workload interactions on attentional resources and performance. This chapter presents a new theoretical model that explains the effects of physical and mental workload combinations on visual and auditory attentional resources (verbal and spatial resources); the model was developed through three experimental laboratory studies. Moreover, the current thesis suggests that the impact of physical and mental workload interactions on visual and auditory task performance is significant, since, as mentioned in Chapter 1, the general aim of this thesis was to create a new model that describes the impact of physical and mental workload interactions on Wickens's (1984) multiple attentional resources model, which includes visual and auditory resources, both verbal and spatial. The findings of the experimental studies and field study in this thesis show that physical and mental workload interactions can positively and negatively influence performance in dual-task situations involving physical load versus visual resources and physical load versus auditory resources. Physical workload can lead to better performance at certain levels of workload combinations, a phenomenon that was previously undiscovered.

Many jobs in the real world require physical activity as well as mental effort; as despite technological advances in various jobs such as assembly tasks, manufacturing, fire-fighting, and the armed forces, these jobs can still place a load on operators' cognitive attentional resources (Mozrall and Drury, 1996). Furthermore, some of these jobs require high visual and/or auditory attention, concentration, and high physical activity, often in challenging environmental conditions. Therefore, this thesis not only investigates the influence of physical and mental workload combinations in a laboratory setting, but also validates and translates the findings from experimental results into a field study (i.e., a product assembly job) to determine the transferability between the experimental and applied results. In addition, this thesis helps to develop guidelines and recommendations for multi-tasking workloads (i.e. physical and mental demands) to assist job designers in considering the important balance between task workload and operators’ attentional limitations in order to achieve best performance, high productivity, and error reduction.

As described in Chapter 2 (see section 2.6), there is a lack of scholarly investigation into the impact of physical workloads on complex and varied levels of mental, visual, and auditory demands. In addition, no study has investigated the impact of workload interactions on multiple perceptual inputs (visual and auditory) (Mozrall and Drury, 1996). Thus, Chapter 4 examined the effect of different levels of physical (cycling activity) and mental workload interactions on visual attentional resources (arithmetic and spatial figure tasks). Chapter 5 then investigated the influence of physical (cycling activity) and mental demand combinations on auditory tasks (arithmetic and tone localisation tasks). Chapter 6 also described the impact of workload interactions on auditory tasks (arithmetic and tone localisation tasks), but changed the physical workload produced to a box lifting task instead of cycling in order to make the experiment more applicable to the field environment. More specifically, based on the findings in Chapters 4, 5, and 6, a significant effect of physical and mental workload interactions on visual and auditory task performance was identified. Thus, an examination of these impacts was translated and validated in an applied setting (assembly job), as explained in Chapter 7.

8.2 OBJECTIVES AND METHODOLOGY

8.2.1 Thesis Objectives

As stated in Section 8.1 and in Chapter 3 (see Figure 3.1), this thesis involves specific objectives other than its primary aim. First, this study investigated whether physical workload interactions with mental workloads could compensate for reductions in attentional resources resulting from the low level of arousal that occurs at a low mental workload, since, as mentioned in Section 2.6, there is a lack of research that identifies the effects of physical and mental workload interactions under different levels of mental workload difficulty. Most previous studies have examined the influence of different physical exercise levels on simple mental tasks (reaction time tasks) but not complex cognitive tasks. Second, the current research examines gender differences in the dual-task paradigm of physical and mental workload interactions; no previous studies have examined gender differences in complex workload task interactions (Yagi et al., 1999). The current research also determines whether physical workload can place stress on brain activity while interacting with mental workload.

8.2.2 Methodological Summary

As stated in Chapter 3 (see section 3.2.2), to determine the effect of physical and mental workload combinations on visual and auditory task performance, the methodology used in the laboratory experiments was divided into three sections. First, the performance measure was the accuracy and time of task. Second, the physiological parameters included heart rate, heart rate variability, and blood pressure, in order to establish physiological arousal effects; these parameters are very sensitive to physical and mental workload level changes. Significantly, the NIRS technology was used as a new neuroergonomics technique in the experimental studies, in order to determine the impact of physical and mental workloads on brain activity by measuring regional cerebral oxygen saturation (rSO2) in the brain. This is a novel technique, used because some researchers have suggested that measuring brain activity with NIRS technology would indicate the stress of workload on information processing, since it reflects the balance between oxygen consumed to perform a task and the actual amount of oxygen delivered (Perrey et al., 2010). Third, subjective assessment tools (the NASA-TLX score and Borg’s CR10 and RPE scores) were used to measure mental workloads and physical, respectively.

8.3 KEY EXPERIMENTAL AND FIELD STUDY FINDINGS

This section shows how the integrated empirical results led to the development of a new theoretical model, which was the aim of this thesis, as mentioned in Chapter 1 (see section 1.4.1). In addition, it presents the validation and translation of the model into a real field setting. The integrated findings of all four studies are divided into four sections:

8.3.1 Performance Measures

Based on the findings of the experimental studies, this thesis addresses the positive and negative effects of workload interactions on accuracy and task time at certain levels of interaction. The integration of experimental results led to these key findings which represent the theoretical developments of the new model outcomes:

- *Low physical × low mental workload interactions lead to better accuracy and task time in visual tasks (arithmetic and spatial figures) and auditory tasks (arithmetic and tone localisation).*
- *Medium physical × low mental workload interactions lead to better accuracy and task time in visual and auditory tasks.*

The results of Chapters 4, 5, and 6 indicate that low and medium physical workloads have a positive impact on visual and auditory resources (verbal and spatial) through leading to better accuracy and task time at low mental workload. Based on the results from these chapters, a low physical workload (20% of Wmax) had a positive impact on visual (arithmetic and spatial figures) tasks; furthermore, the low physical workload (20% of Wmax-cycling and 8% of body mass-lifting task) had a positive effect on auditory (arithmetic and tone localisation) task accuracy and time of task variables while interacting with the low mental workload. Since, the low physical workload led to better performance at the low mental workload in visual and auditory tasks. According to the results in Chapter 4, the spatial figures task showed lower accuracy than arithmetic tasks at rest level of a low mental workload (see section 4.2.1), whereas the differences between the visual tasks disappeared while interacting with a low physical load. Furthermore, there were no significant differences between the visual tasks in accuracy or task time at low and medium physical levels in low mental workload conditions. In addition, a medium workload of physical activity (50% of Wmax-cycling and 14% of body mass-lifting task) led to better accuracy and task time in both auditory tasks at low mental workload. Generally, the results in Chapters 5 and 6 were quite similar; according to the findings, there were no significant differences between the auditory tasks in accuracy and time of task at low and medium physical workload levels in low mental workload conditions because the physical workload leads to an increase in the level of arousal, which has a positive impact on visual and auditory information processing: the better speed of answers and accuracy occur. These results are consistent with previous researchers' results, which indicate that a medium level of physical exercise supports performance in visual psychomotor tasks (Reilly and Smith, 1986) and auditory tone reaction time tasks (Audiffren et al., 2008) due to increased arousal levels. Moreover, the results show that physical activity has a significant impact on oxygenation changes in the brain (rSO2), since the increases in physical activity loads lead to a reduction in oxygenation changes, by translating more oxygen to the brain. Therefore, the cognitive task load on activation reduces, and visual and auditory information processes at low mental workloads are facilitated, leading to better performance. Thus, the new theoretical model illustrates that low and medium physical workloads lead to better performance in visual tasks (verbal arithmetic and spatial figures) and auditory tasks (verbal arithmetic and spatial tone localisation) at low mental workload.

Moreover, the result in the field study is consistent with the new model outcomes, since task time at low physical and low mental workload (mirror assembly task) improves; the actual task time is lower than the standard time. However, the impact of physical and mental workload interactions in assembly tasks on accuracy is at ceiling; there are no significant differences in accuracy between the three assembly task conditions, as shown in the Chapter 7 results. However, this might reflect the significant experience of the operators in performing these tasks (skilled operators).

- *Low physical × medium mental workload interactions lead to better accuracy in visual tasks and better task time in visual and auditory tasks.*
- *Medium physical × medium mental workload interactions lead to better task time in visual tasks.*

According to the results given in Chapter 4, a low physical workload (20% of Wmax) is beneficial for medium mental workload since the low physical load leads to better accuracy and time of task in both visual tasks. More interestingly, the participants observed better time of task at the medium physical load (50% of Wmax) versus medium mental workload in visual tasks but not the best; there were no significant differences between times in either visual task at low and medium mental workloads at the medium physical activity. In contrast, there was a significant difference in time between low and medium mental workloads at the baseline condition in both arithmetic and spatial figures tasks (see first pilot study, section 4.2.1). In contrast, the findings in Chapters 5 and 6 indicate that a low physical workload (20% of Wmax-cycling and 8% of body mass-lifting task) does not lead to better accuracy, but it does lead to better task times in both auditory tasks at medium mental demand since, there were no significant differences in times between low and medium mental workload levels. Interestingly, the results of the current study illustrate that low physical workload (20% Wmax) led to better time of task in both arithmetic and tone localisation while interacting with medium mental workload. In contrast, there were significant differences between times at low and medium mental demand levels in both tasks under the baseline condition (pilot study, section 5.2.4). Moreover, a medium level of physical load (50% of Wmax-cycling and 14% of body mass-lifting task) did not lead to better performance in auditory tasks at medium mental demand. Therefore, the current thesis suggests that low physical workload leads to better accuracy and task time in visual tasks at a medium mental load, whereas it only leads to better time of task in auditory tasks at a medium mental load. In addition, it indicates that a medium physical load leads to better task time in visual tasks at a medium mental load, although this might be because an auditory task is more difficult than a visual task, a conclusion supported by other research. Auditory tasks need more information processing and time, such as recalling data from long-term memory (Halpern, 2000; Yagi et al., 1999). The new theoretical model suggests that better performance at a medium mental workload level in visual and auditory tasks occurs due to the increasing level of arousal produced by physical activity; since incremental increases in physical activity lead to increased levels of arousal (Mozrall and Drury, 1996), the cognitive visual and auditory information processes become better (Audiffren et al., 2009). Furthermore, arousal increases as physical workload increases from low to medium level, which leads to a decrease in rSO2 since more oxygen transfers to the brain. This means the percentage of oxygenation in the brain decreases, so the amount of oxygen in the brain becomes equal to the amount of oxygen needed to complete the mental demand. Therefore, low and medium physical workloads lead to better cognitive information processing at low and medium mental loads.

However, the effect of physical loads on both visual tasks at all levels is positive since there are no significant differences in accuracy and task time between both tasks at these levels of interaction, as presented in Chapter 4. Contrarily, the results in Chapters 5 and 6 show significant differences between times in both auditory tasks at a high physical load with medium and high mental auditory workloads. The arithmetic task requires more time than the tone localisation task at these levels of interaction. This could be because the arithmetic task used in these experiments was more complex than the tone localisation task. The current research suggests that high physical workload negatively affects results for auditory arithmetic tasks (verbal task). Since, there is still a significant difference between both auditory tasks in time of task at high physical and mental workload interactions as well as in baseline condition. Therefore, the current model suggests that physical workload is allocated to Wickens' 'auditory verbal resource pool'.

Based on the results of the field study (see Chapter 7), the better time of assembly task at a medium physical level with a medium mental workload (bumper assembly task) observes, since the actual time of this assembly task is lower than the standard time. Therefore, this result is consistent with the new model predictions since, as mentioned previously, medium physical workload leads to better task time in both visual tasks at medium mental workload.

- *The participants' worst performance occurs with high physical × high mental workload interactions (overload) in both visual and auditory tasks.*

Across all experimental studies, the participants' worst performance appeared in visual and auditory tasks with overloaded levels of physical and mental workload interactions due to high levels of arousal, since the HR increases significantly. In addition, the impact of high physical load on rSO2 is a ceiling impact, since there are no significant differences between medium physical load and high physical load in rSO2. This means that at high physical loads no more oxygen is delivered to the brain, so the oxygenation in the brain increases due to high mental workload, which creates an imbalance between the amount of oxygen in the brain and the amount of oxygen required to complete the task. This may be because other parts of the body (e.g. arm and leg muscles) consume oxygen at the same time as it is needed by the brain (Perrey et al., 2010). However, the new model indicates that there is a positive interference between physical load and visual tasks, since there are no significant differences in performance between the visual tasks at high the levels of interaction, whereas there are differences between the tasks at baseline with a high mental load. In contrast, the auditory arithmetic task requires more time than the tone localisation task at high levels of interaction, the same as at the baseline level. At medium and high mental loads the auditory arithmetic task took longer than the tone localisation task (see pilot study, section 5.2.4), indicating that the high physical workload negatively influenced the auditory verbal task, so there is no interference between physical activity and auditory verbal resources at high levels of workload interaction.

In the field study, the effect of physical and mental workload combinations on accuracy in assembly tasks hits a ceiling; there are no significant differences in accuracy between the three assembly task conditions, as shown in the results in Chapter 7. However, this might reflect the high experience level of the operators in performing these tasks (skilled operators). In contrast, task time significantly increased with a high physical workload combinations (door assembly task); there were no significant differences between the actual time of the door assembly task and the standard time. This is consistent with previous research results, which showed that increased physical workload leads to high arousal, resulting in performance decrements (Audiffren et al., 2008). One of the important results of this research is that the results of experimental studies and the field study are consistent: The patterns of task time in the field study under three assembly situations are the same as those found in laboratory experiments. These results ultimately suggest that high levels of workload interactions lead to worst performance.

In terms of gender, the findings in chapters 5 and 6 show that differences occur in the auditory arithmetic task at high physical load with medium and high mental arithmetic tasks and at medium physical loads with high mental arithmetic tasks.

Females needed more time than males to complete the arithmetic task under these levels of interaction. That might be because the arithmetic task was more complex than the tone localisation task. In addition, the strength and maximum workload capacity of males is greater than females (Borg, 1998). These results are consistent with Yagi et al. (1999), who mentioned that the performance of males at high physical loads is better than females in terms of auditory task time reaction.

8.3.2 Physiological Parameters

Based on the results of Chapters 4, 5, and 6, the HR, HRV, and MBP parameters are sensitive to physical and mental task workload interaction changes. Also, these measures verify the difficulty levels of both physical and mental workloads across all experimental studies in the current research. HR and MBP increase significantly as workload interactions increased. Thus, increased levels of workload combinations lead to increased HR, which means the arousal level increases while physical and mental workloads increase in both visual and auditory tasks. In Chapter 4, the HR in the spatial figures tasks is higher than in the arithmetic tasks at the baseline condition (section 4.2.1). In contrast, there are no significant differences between the two visual tasks in HR when interacting with a physical load. Also, in Chapters 5 and 6, the HR in auditory arithmetic tasks is higher than tone localisation tasks at baseline conditions (section 5.2.4). In contrast, there are no significant differences in HR for either of the two auditory tasks when interacting with physical loads. Previous authors have shown that high levels of physical demand and cognitive auditory tasks increase stress on the cardiovascular system, leading to an increased heart rate (Audiffren et al., 2009; Kamijo et al., 2004). The current thesis suggests that physical workload leads to better performance in cognitive visual and auditory tasks because of changes in the level of arousal, which is reflect by changes in HR. According to the field study results, HR indicators verify the difficulty levels of the three assembly tasks (mirror, low; bumper, medium; doors, high). HR data show significant differences between low, medium, and high levels of difficulty. Arousal levels increase as the assembly workload increases. This result is consistent with the experimental results of the current research. The current thesis suggests that the HR variable is a valuable objective measure in the field domain to indicate workload interaction effects.

As the experimental results describe in Chapters 4, 5, and 6, the HRV measure increases as physical workload increases, but decreases as visual and auditory mental workloads increase. In the Chapter 4 results, there is no significant difference between HRV at low and medium visual mental demands under low physical workload. This might suggest that physical workload leads to better performance at these levels. Moreover, there is a significant difference between the visual tasks (arithmetic and spatial figures) in HRV at baseline conditions, but these differences disappear at the low and medium physical workloads with low and medium mental workloads. In Chapter 5 (section 5.2.4), the pilot study shows significant differences in HRV between the auditory tasks at all three levels of difficulty; arithmetic tasks were associated with lower HRV than tone localisation tasks. In contrast, the results presented in Chapters 5 and 6 show no significant differences between these tasks with low and medium physical workloads. According to Veltman and Gaillard (1996), the HRV measure is very sensitive to complex mental tasks, so HRV decreases significantly as mental workload increases. At the high levels of physical and mental workload interactions, however, HRV significantly decreases in the visual spatial figures task rather than the visual arithmetic task; and in the auditory arithmetic task rather than tone localisation. This research suggests that high physical workload negatively affects the spatial figures task (visual-spatial) and auditory arithmetic task (auditory-verbal) since, it leads to worst performance due to the high level of arousal.

In terms of gender differences, the results in Chapter 4 indicated that females had higher HR and MBP than males during the spatial figure tasks at high physical workloads with low, medium, and high mental workloads, and medium physical workloads with high mental workloads. In addition, in Chapters 5 and 6, the results showed that females had higher HR and MBP than males in auditory arithmetic tasks at high physical workloads versus low, medium and high mental workloads and medium physical workloads versus high mental workload. This is consistent with Yagi et al. (1999) who found that females have higher HR measures than males and higher visual reaction time at high levels of physical activity. This may be because females need more time to complete the auditory arithmetic mental tasks. Also, physical workload capacity and range of strength in males are greater than for females (Borg, 1998), so the physical loads may affect females' physiological state.

8.3.3 Brain Activity

As stated in Chapter 1 (section 1.3.1), the novel potential physiological physical and mental workload measure was used in the current thesis as a new neuroergonomics method to reflect the impact of physical and mental workload interactions on attentional resources by measuring the effect of workload on brain activity. This is the first time the NIRS method has been used in this type of study; most previous studies have used this technology to reflect the impact of physical workload on muscle activity and mental workload on brain activity separately (Perrey et al., 2010). Changes in oxygenation in the frontal lobe and motor cortex in the brain may reflect workload level and capacity (Perrey et al., 2009). NIRS is used to measure rSO2, which reflects the oxygenation changes in the brain as a task is performed. The NIRS method was used in the current research in the laboratory experiments to measure brain activity as physical and mental tasks were performed (section 3.2.2).

As the results in Chapters 4, 5, and 6 show, rSO2 is sensitive to physical workload changes and mental tasks, visual (arithmetic and spatial figures), and auditory (arithmetic and tone localisation) workload changes. The effect of physical and mental workload interactions on rSO2 is significant; it increases significantly as mental workloads, visual, and auditory, increase. In contrast, an increasing level of physical workload led to decreases in the rSO2 percentage. This result is consistent with Perrey et al. (2009), who suggested that an increasing level of physical exercise affects information processing by increasing blood flow to the brain; therefore, the amount of oxygen delivered to the brain increases and leads to better cognitive functions. The increasing rSO2 measure indicated that the percentage of oxygenation changes in the brain was due to an increased level of mental workload. This means the amount of oxygen in the brain does not equal the quantity necessary to meet the mental workload in either mental task. In contrast, increasing the level of physical load led to a decrease in the oxygenation changes by transporting more oxygen to the brain through blood flow. This might create a balance between the availability of oxygen in the brain and the amount required to complete the auditory task. This could explain why mental performance was better at the low and medium physical activity loads. However, according to the results of the laboratory experiments in this study, the effect of high physical workload on rSO2 reveals a ceiling effect at medium and high mental workloads because there is no significant difference in rSO2 at medium and high physical loads versus medium and high mental workloads. That may be because other body parts (e.g. arm and leg muscles) consumed oxygen at the same time it was needed by the brain (Perrey et al., 2009). The effect of gender differences on rSO2 was not significant.

The current thesis suggests that the rSO2 measure is a valuable objective measure that reflects the effect of dual-task demands on brain activity. In addition, it validates the NIRS technique as a novel method to evaluate the effects of physical and mental workloads on attentional resources and brain oxygenation changes in a multi-tasking paradigm.

8.3.4 Subjective Assessment Tools

Physical Workload Assessment Tools (Borg's scores)

As stated in Chapter 3, the Borg-CR10 and RPE scales were used in the laboratory experiments and field study to evaluate the effect of physical workload levels. Based on the results given in Chapters 4, 5, and 6, the Borg-CR10 and RPE scores were significantly affected by physical demand changes, whereas the effect of mental workloads for both visual and auditory tasks did not affect the scores. The increasing scores in both scales were associated with the physical workload increasing and indicated the sensitivity of the scale and human perceptions to changes in physical workloads. These results are similar to those in Chapter 4, which presented a significant influence on CR10 and RPE of physical cycling loads and significant differences between the physical levels. However, the scores were not sensitive to visual auditory arithmetic and tone localisation mental workload changes because the participants' perceptions during the workload interactions were not affected by mental workload changes. These results are similar to the findings of Fredericks et al.

(2005), who concluded that the Borg scales were sensitive to physical loads levels, whereas the changes in cognitive word test and arithmetic task workloads did not impact the CR10 and RPE scores. That means that mental activities do not influence participants' perception of physical workload evaluation using subjective physical assessment tools. Generally, the current thesis findings indicated that the a moderate positive correlation ($p < 0.05$) between CR10 and RPE scores, which means that the increasing score of CR10 is associated with an increased RPE score. Both scores were significantly linear and increased with an increase in physical workload since HR increased. Hence, any elimination for either score would not impact the research findings negatively. However, based on the field study results, the Borg scales are sensitive to the three levels of physical assembly loads (mirror, bumper and doors) as illustrated in Chapter 7 and are consistent with the experimental studies' results. In addition, the scales justify and verify the three levels of assembly physical workload that were adopted in the field study. Thus, the current thesis recommends that Borg's scales are fit and appropriate subjective measures to use in the real domain to reflect physical activity loads in such assembly jobs.

In terms of gender differences, according to the results in Chapters 4, 5 and 6, females report higher scores than males in both CR10 and RPE scales. The significant differences between genders occurred at high physical workloads in the cycling task and in the box lifting task under medium and high levels of physical workloads, which again may be because maximum workload capacity and muscle strength are greatest in men (Borg, 1998).

NASA-TLX Assessment Tool

The NASA-TLX is used to evaluate the effect of mental workload levels. In addition, the mental demand (MD) dimension and physical dimension (PD) in the NASA-TLX were considered in the analysis as the purpose of this research was to find the effect of physical loads on subjective mental demand assessments as stated in Chapter 3 (section 3.2.5.4),.

In terms of MD, the results of chapters 4, 5, and 6 show a significant sensitivity and impact on MD by mental workload difficulty changes (low, medium, and high) in visual and auditory tasks. The results of the three experimental studies in this thesis are consistent. The mental subscale score increases as mental, visual, and auditory workloads increase, whereas, it is not influenced by physical workload difficulty changes (cycling and lifting tasks). Furthermore, the effect of physical and mental workload interactions on MD was not significant. The data analysis in this chapter was consistent with previous studies that found the NASA-TLX was sensitive to changes in mental auditory demand difficulties (DiDomenico and Nussbaum, 2008; Ferdericks et al., 2005).

These results suggest that participants' perceptions about mental load while performing mental auditory activities simultaneously with physical activity was not impacted by physical activity. Furthermore, simultaneously introducing a physical workload does not appear to alter perceptions of mental workload. This means the participants did not perceive a change to their perceptions through physical activity so, there was no impact on subjective mental demand assessment from physical loads. In terms of PD, the results of the experimental studies showed that the subscale was sensitive to physical workload changes, whereas it was not sensitive to mental workload changes. This means that participants distinctly perceived physical demands and rated them appropriately on the PD subscale. According to the results of the field study (Chapter 7), MD is affected by physical workload while PD is influenced by mental workload in assembly tasks; however, this could be because the field study was constrained in the number of conditions (three workload conditions). If more than three conditions were used, the analysis may present different results.

In terms of overall NASA-TLX ratings, the results given in Chapters 4, 5, and 6 show that the TLX is sensitive to increasing physical and mental workloads in visual and auditory tasks. Astin and Nussbaum (2002) and Frederick et al. (2005) used the NASA-TLX rating to evaluate the impact of different levels of physical activity on visual and auditory cognitive processes; they determined that rating scores increased as physical and mental demands increased. Thus, the results in this thesis suggest that there is a significant contribution of physical workload to overall TLX ratings, similar to mental workload. The overall TLX score increased as physical loads increased. That may be because physical activity affects the TLX dimensions of performance, effort, and time subscales.

For these reasons, the overall TLX score increased. Other researchers may wish to consider the influence of physical workload while using the TLX to evaluate the mental workload level in tasks that include physical components, as most previous researchers have used the TLX to measure mental workload demands and have neglected the impact of physical loads. However, the field study (Chapter 7) results found that, overall, the TLX verifies the three assembly workload levels used in the field study (mirror assembly, low workload level; bumper assembly, medium level; and door assembly, high level) that were assumed in the study. The overall TLX score increases as the assembly workload increases. The results of the field study are consistent with the experimental setting results. Therefore, the current thesis suggests that the TLX score is a suitable subjective measure to evaluate overall workload in such jobs. In addition, the NASA-TLX is reliable to implement in the real domain to reflect multi-task workloads (Baulk et al., 2007). In this research, the NASA-TLX measure used was the total unweighted workload.

In terms of gender differences, there were no significant differences between male and female participants in MD rating scores in visual and auditory tasks. Similarly, there were no significant gender differences in overall TLX score.

8.4 RESEARCH CONTRIBUTIONS

This PhD research achieved the aim and objectives delineated in Chapter 1, section 1.3.1. The main aim of this research is to understand the interaction effects of different levels of physical and mental workload on attentional resources along two of Wickens' (2008) dimensions, input modality (visual vs. auditory) and processing code (verbal vs. spatial), and performance based on the two mechanisms of improvement arousal and blood oxygenation changes in the brain, since the physical workload leads to more blood going to the brain (Perrey et al. 2010) as presented in Chapter 1, section 1.3.1.

- **Objectives 1, 2 and 3**

As outlined in the literature review (Chapter 2), numerous papers have investigated the effect of physical and mental demands on individual performance, independently. The current thesis creates a new model that explains the impact of physical and mental workload interactions on visual and auditory attentional resources through conducting a series of experimental studies to investigate the effects of different levels of physical and mental workload combinations on visual resources (arithmetic task - verbal and spatial figures task - spatial), as presented in Chapter 4. Previous research has examined the effects of different physical loads on simple visual tasks (reaction time tasks) or on one mental demand level (Tomporowski, 2003). The effect of various levels of physical and mental demands on multiple resources, as modelled by Wickens (1984), has not been previously examined (Mozrall and Drury, 1996). Moreover, previous authors have not evaluated the impact of physical and mental workload interactions on complex auditory tasks (Audiffren et al., 2009). Thus, this thesis covers the impact of various levels of physical and mental workload combinations on auditory resources, (auditory arithmetic task-verbal resource, tone localisation task-spatial resource), as detailed in Chapters 5 and 6.

According to Chapter 2, another important aspect is the correlation between mental workload and performance. Previous authors reported that the relationship between mental workload and performance is an inverted-U, which is the same as the relationship between arousal and performance (Young and Stanton, 2002[a]). Thus, a low mental workload can lead to performance problems due to shrinkage in attentional resource capacity at a low level of arousal. The interactions between low mental workload and physical load with Wickens (1984) model dimensions have not been previously examined. The current thesis addresses how medium physical load positively affects low mental workload level in visual and auditory tasks by increasing the level of arousal, as stated in Section 8.3.1. Some papers have mentioned that the correlation between physical activity and cognitive tasks produces a curved line due to the increasing levels of physical workload. (Audiffren et al., 2009).

Another interesting aspect of the current research is that it extended the investigation to provide a deeper understanding of the effect of physical and mental workload from a brain activity (physiological) perspective by measuring the regional cerebral oxygen saturation (rSO2) using new technology (NIRS method) as a new neuroergonomics method. According to Perrey et al. (2009), no previous study has examined the effect of physical and mental demands on brain activity. Both physical and mental workload interactions have a clear effect on brain activity. Specifically, rSO2 increases significantly as mental, visual, and auditory loads increase. In contrast, rSO2 decreases as physical workloads increase. This means the amount of oxygen delivered to the brain increases (percentage of oxygenation change decreases). The current thesis proposes that the NIRS method is a valuable technique to reflect the influence of physical and mental workloads on attentional resources.

Some levels of physical workload can be beneficial to visual and auditory resources (verbal and spatial) by leading to better performance at some levels of mental workloads. On the other hand, they can negatively impact (i.e., worse performance) some levels of visual and auditory demands as a result of two main issues: physiological arousal level and brain oxygenation changes, as mentioned in Section 8.3. As discussed in Section 8.3.1, the theoretical model was developed with the following main design guidelines derived from this model:

- *Low physical load leads to better performance in visual and auditory resources (verbal and spatial) at a low mental workload.*
- *Medium physical load leads to better performance in visual and auditory resources (verbal and spatial) at the low mental workload.*
- *Low physical load only leads to better accuracy in visual resources (verbal and spatial) and task time in visual and auditory resources at a medium mental demand.*
- *Medium physical load leads to better task time in visual resources tasks at a medium mental workload.*

- *Worst performance occurs with the physical and mental overload interactions in visual and auditory resources (verbal and spatial).*

These guidelines will lead to improved job system design in dual-task systems, in terms of task workload balance and operators' attentional resource capacity. Moreover, it is necessary to mention that high physical workload negatively impacts auditory verbal resources (arithmetic task) at medium and high mental workloads. As discussed in section 8.3.1, that means interference between high physical load with medium and high mental auditory loads. Therefore, the current thesis suggests that:

- *Physical workload draws on auditory verbal resources, since high physical loads lead to worst verbal auditory task performance at medium and high mental workloads.*
- *Physical workload is beneficial for visual resources (verbal and spatial tasks) and auditory spatial resource in the multiple resources model by Wickens (1984).*

The main contribution of this research is the development of a theoretical model in terms of the multiple attentional resources model which addresses the issue that the physical workload occupies resources from the auditory-verbal resource pool, as opposed to being a separate pool of resources in the multiple resources model by Wickens (1984) as shown in Figure 8.1. Also, physical workload is beneficial for visual resources (verbal and spatial) and auditory-spatial resources. This model explains the effects of physical and mental workload interactions on input perception of the attentional resources model, which will add valuable information to the ergonomics literature in terms of physical and mental workload impacts, especially since there are no previous studies that concern the influence of workload interactions on the MRM.

Perhaps of particular interest, the current thesis uses different methods to evaluate the effects of physical and mental workload interactions on individual performance. Most previous research has used performance and heart rate (Frederick et al., 2005). However, the current thesis uses three methods: (1) performance (accuracy and task time), (2) physiological parameters (HR, HRV, and MBP), and brain activity (NIRS method), and (3) subjective assessment tools (NASA-TLX scale, and Borg's CR10 and RPE scales).

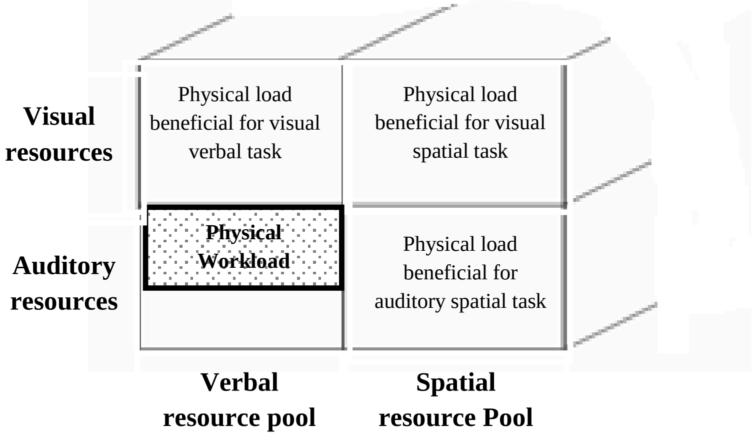

Figure 8.1 The effect of physical workload on Wickens' multiple resources model

- **Objective 4**

The current thesis determines the differences between genders by accounting for gender in performing the physical and visual mental tasks concurrently. In addition, it considered gender while participants performed physical and auditory mental tasks concurrently. Therefore, the results of the current thesis can be generalised, which will help other researchers to understand the links between gender differences performing similar tasks (dual-task paradigms). Historically, the gender aspect has been neglected, which may have affected previous findings (Yagi et al., 1999).

More importantly, this thesis validates and translates the experimental studies setting (simulated) into a field setting (actual). It included a field study of truck factory assembly tasks (Mercedes factory) in order to investigate the effects of physical and mental workload interactions on operator performance in assembly jobs. The results of the field study are consistent with the experimental studies. Moreover, the thesis addresses output measures (time of task, HR, and NASA-TLX tool) and Borg's scales used in the field study to verify that the three levels of assembly workload and were reliable and valuable. Thus, these findings suggest that these measures are suitable and appropriate to implement in the field to evaluate the physical and mental workload interactions of jobs for further research on such jobs.

However, according to the new model guidelines, as mentioned previously, the Mercedes factory should consider redesigning its assembly task system in the door assembly job since this is considered an overload workload interaction, so the worst time of task is observed with the current door assembly workload. Therefore, the factory needs to reduce the physical and mental workload in this task in order to lead to the better time of task by redesigning the work system (e.g., by adding a conveyor system to carry the door instead of manual lifting) to reduce the physical load on the operator or reducing the mental load by letting another operator support the assembly task.

In general, in jobs which include physical and mental workloads, designers should aim to reduce the physical workload to a low or medium level with visual tasks (verbal and spatial) that need low or medium visual mental load, through the use of automation and technology (e.g. automatic lifting hand or controlled trolley to carry heavy parts, to reduce the physical activity). In jobs that require physical and auditory mental workloads, designers should improve the work system by reducing both physical load and mental auditory workload to a low level, to gain better performance (accuracy and time of task), since they can reduce the physical load through letting another operator assist in the physical activity or carry any additional load so the physical workload is reduced.

8.5 RESEARCH LIMITATIONS

One limitation that should be noted is that all participants in the experimental studies were staff and students of Brunel University, aged 25 to 35 years old, and were considered healthy. The results of this research cannot necessarily be generalised to all populations such as young or elderly groups. The physical tasks used in the experimental studies may have been affected by age (Louhevaara and Kilbom, 2005), and mental task performance may also be affected by age (Matthews et al., 2000). Because of this, it is possible that individual differences caused the large standard deviations and resulted in non-significant differences between certain measures.

According to Tomporowski and Ellis (1986), different types of mental tasks can influence performance and information processes; therefore, most previous research on the effect of physical load on cognitive information processes has failed to obtain uniform results. In this research, the complexity of visual tasks (arithmetic and spatial figures tasks) and auditory tasks (arithmetic and tone localisation tasks) may impact the results since it is challenging to control the difficulty level across visual and auditory tasks. Therefore, the types of tasks might impact the findings; for example, the auditory tasks seemed to be more difficult than the visual tasks.

In the field study, other factors might have affected the results. For example, the possibility of environmental stressors (e.g., temperature and noise), creating a carryover effect was not examined (Wickens and Holland, 2000). Given the possibility of environmental and other factors (e.g. costs), using additional physiological measurements was problematic. Therefore this study used only heart rate. In addition, this study used a small sample size because controlling the number of participants in a real-world situation is difficult. The possibility of a carryover effect was not investigated.

Finally, it was not possible to examine all aspects of interactions of mental and physical workload conditions through the field study, as it was in the laboratory experiments. Therefore, the assembly task workload conditions used in the field study were limited to reflecting the different physical and mental workload combinations available in the factory. Three physical and mental workload interaction levels were represented. Alternative types of assembly tasks or other industrial fields are recommended for future study. In this real world scenario, the number of physical and mental workload interactions was constrained to three levels since it was difficult to set up the same nine conditions in the laboratory-based studies in the field study. However, the effect of physical workload on mental demand was significant because the field study was constrained to three levels, so if there were more than three levels of workload interactions, the effect of physical workload may not have been significant. In these three assembly workload interactions, the physical and mental workload was linked linearly, which may affect the results.

8.6 FUTURE WORK AND RECOMMENDATIONS

This PhD thesis investigates the impact of physical and mental workload interactions on visual attentional resources (verbal arithmetic task and spatial figures task) and auditory resources (verbal arithmetic task and spatial tone localisation task). In addition, it applies the results of the experimental studies in the field (assembly job) to validate and translate the experimental setting to a practical setting. One future research direction would be to change the visual and auditory mental tasks and physical tasks by examining other types of jobs in real environments.

- **Test results for different types of visual and auditory mental tasks.**

This research used two types of mental visual tasks: arithmetic tasks to reflect the verbal resource and spatial figures tasks to reflect the visual-spatial resource. In addition, it used two types of mental auditory tasks (verbal arithmetic task and spatial tone localisation task). This research finds positive effects of physical and mental workload interaction on visual and auditory tasks. According to Tomporowski (2003), the findings of previous papers on the effect of physical exercise on cognitive tasks are not uniform; individual performance depends on the type of mental task and its complexity. Therefore, it is recommended that future researchers investigate the effect of workload interactions on other types of visual and auditory mental tasks.

- **Test results for different types of physical tasks.**

This research used cycling and box lifting tasks to produce physical workloads. According to Mozrall and Drury (1996), the effect of physical loads on cognitive information processes may depend on the nature of the physical activity. Thus, other research would do well to use other types of physical tasks that are more applicable to real work environments, such as running and jogging, since these tasks are more reliable and practical for certain professions, such as military and fire-fighting jobs.

- **Use of the NASA-TLX rating score as a subjective tool for overall workload.**

This research finds the NASA-TLX to be a useful subjective assessment tool, not only for mental workload, but also for mental and physical workload interactions combined. Consequently, it recommends that future research should consider the utility of the TLX scale to other types of physical and mental task workload combinations.

- **Test findings for a wider age group.**

As mentioned in section 8.5, all participants in the experimental studies were staff and students of Brunel University, aged 25 to 35. Therefore, it would be worthwhile covering another age group (e.g. the elderly) in future research to make the findings more generalisable. According to Halpern (2000), age does influence verbal and spatial cognitive task performance. Moreover, Borg (1998) said that young adults possess more strength in their muscles and have a higher maximum workload capacity than older individuals. Thus, it is possible that individual differences will show a bias when attempting to apply the established physical and mental task design in this thesis to other age groups.

- **Test findings for other real jobs.**

The current thesis translates and validates the experimental studies to an assembly job. This study examines the impact of physical and visual mental workloads of assembly tasks on operator performance. The results are consistent with experimental settings. The measures used in the field study (time of task, HR, TLX, and Borg scales) were found to be reliable and suitable. Thus, it is recommended that further study might investigate results in other practical settings to verify the results of this research. For example, researchers might wish to investigate the effect of physical and mental workload interactions on performance in different jobs, such as the armed forces, fire-fighting, and driving.

8.7 CONCLUSION

The current thesis creates a new theoretical model and guidelines that explain the impact of physical and mental workload interactions on input perception resources proposed in Wickens's (1984) multiple resource model for verbal and spatial resources, both visual and auditory. Furthermore, it suggests a positive effect between physical workload and mental workloads on visual and auditory task performance at certain levels of workload combinations through a number of experimental studies, particularly at low levels of workload interactions which lead to better performance, while other workload interactions lead to worse performance on cognitive tasks. However, when physical activity was introduced, performance at the medium level of mental workload was equivalent to that in the low mental workload condition; furthermore, at the low mental workload, there were no differences in performance between low and medium physical workloads. The general pattern of results suggests that physical workload leads to better performance in these medium-demand conditions up to the higher level in the low-demand condition. The thesis demonstrates the links between physical loads and physiological arousal and brain oxygenation in visual and auditory cognitive information processing improvements. This thesis explains the correlation between physical and mental workloads in dual-task scenarios, which allows job designers to consider the important balance between overall task workload and individual attentional resource limitations, especially in multi-task demand situations. Thus, the thesis suggests that the work system of dual-task job designers should consider technology, but they also need to balance operators' attentional resource limitations and overall workload as a core factor in design. Therefore, the current thesis provides guidelines that will help designers improve jobs. In addition, it will enhance information in ergonomics through physical and mental workload combinations and individual attentional resource capacity.

Furthermore, this thesis presents the links between gender and dual-task paradigms (i.e., visual and auditory tasks performed concurrently with physical activity) and how physical exercise negatively affects female performance, especially at high workload interactions with auditory arithmetic tasks paired with physical activity (cycling and lifting tasks). These results will help bridge this gap in ergonomics literature and help to generalise the data.

Interestingly, the thesis confirms that the NIRS technology is a valuable and useful neuroergonomics tool that reflects the effect of physical and mental workload interactions on attentional resources by measuring rSO2, which indicates the percentage of brain oxygenation during brain activity. Therefore, it is recommended that other researchers consider using this method to evaluate the influence of physical and mental loads on brain activity, especially in other types of physical and mental workload interactions.

Moreover, this research conducted a field study and investigated the effect of physical and mental workloads in assembly jobs on operator performance. This study serves to validate and translate the results of the three experimental studies to a practical setting. Results of the field study suggest that the proposed measures of performance, HR, and subjective assessment tools (TLX, Borg’s CR10 and RPE scales) are suitable and reliable in applied settings to assess the effect of physical and mental demand combinations on performance.

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Appendices

Appendix A	Research Operational Definitions.
Appendix B	Participants Health Questionnaire.
Appendix C	Participant Information Sheet and ethical approval of effect physical and mental workloads interactions on visual tasks- *First Experiment*
Appendix D	Participant Information Sheet and ethical approval of effect physical and mental workloads interactions on auditory tasks- *Second Experiment*
Appendix E	Participant Information Sheet and ethical approval of effect physical lifting and mental workloads interactions on auditory tasks- *Third Experiment*
Appendix F	Informed Consent Form.
Appendix G	NASA-TLX Score Rating.
Appendix H	Borg’s CR10 and RPE Scales
Appendix I	Summary of descriptive statistics (mean ± SD) for all measures across all experiments as well as across all nine physical and mental workload interactions conditions.

Appendix A

Research Operational Definitions

Physical Workload: '…the demands associated with tasks that require physical work from the operators, thereby utilizing the musculoskeletal system, the cardio-respiratory system, and the nervous system of the human body' (Louhevaara and Kilbom, 2005).

Mental Workload: 'The mental workload of a task represents the level of attentional resources required to meet both objective and subjective performance criteria, which may be mediated by task demands, external support, and past experience.' (Young and Stanton, 2004)

Arousal: Arousal can be defined as the overall state, level of activity, and behaviour of an individual in response to different environmental stressors (e.g. task workload) that activate the nervous system (Matthews et al., 2000)

Attentional Resources: The amount of energetic and structural capacity that needed to complete the cognitive activity and information process (Matthews et al., 2000). The multiple attentional resources model includes four dimensions: modalities (visual and auditory), codes dimension (spatial and verbal), stage (central processing and responding) and responses (manual and vocal) (Wickens, 1984).

Near-Infrared Spectroscopy (NIRS): NIRS is an effective and non-invasive technique that permits the measurement of the percentage of oxygenation and deoxygenated haemoglobin in brain blood and muscles during task performance and at rest (Perrey et al., 2010).

Appendix B

Health Questionnaire

PRE-PARTICIPATION HEALTH CHECK QUESTIONNAIRE

Health and safety within this investigation is of paramount importance. For this reason we need to be aware of your current health status before you begin any testing procedures. The questions below are designed to identify whether you are able to participate now or should obtain medial advice before undertaking this investigation, Whilst every care will be given to the best of the investigators ability, an individual must know his/her limitations.

Subject name: ………………………………………………………………………………………

Date of birth: ………………………………………………………………………………………...

Doctors Surgery Address: ……………………………………………………………………………

Emergency Contact Name: ……………………………………………………………………………

Please answer the following questions:	**YES**	**NO**
1. Has your doctor ever diagnosed a heart condition or recommend only medically supervised exercise?	☐	☐
2. Do you suffer from chest pains, heart palpitations or tightness of the chest?	☐	☐
3. Do you have known high blood pressure? If yes, please give details (i.e. medication)	☐	☐
4. Do you have low blood pressure or often feel faint or have dizzy spells?	☐	☐
5. Do you have known hypercholesteremia?	☐	☐
6. Have you ever had any bone or joint problems, which could be aggravated by physical activity?	☐	☐
7. Do you suffer from diabetes? If yes, are you insulin dependent?	☐	☐
8. Do you suffer from any lung/chest problem, i.e. Asthma, bronchitis, emphysema?	☐	☐
9. Do you suffer from epilepsy? If yes, when was the last incident?	☐	☐
10. Are you taking any medication?	☐	☐
11. Have you had any injuries in the past? E.g. back problems or muscle, tendon or ligament strains, etc…	☐	☐
12. Are you currently enrolled in any other studies?	☐	☐
13. **I have already participated in a blood donation program**	☐	☐
14. Are you a smoker?	☐	☐
15. Do you exercise on a regular basis (at least 60 min a week)?		

16. Describe your exercise routines (mode, frequency, intensity/speed, race times):

If you feel at all unwell because of a temporary illness such as a cold or fever please inform the investigator. Please note if your health status changes so that you would subsequently answer YES to any of the above questions, please notify the investigator immediately.

I have read and fully understand this questionnaire. I confirm that to the best of my knowledge, the answers are correct and accurate. I know of no reasons why I should not participate in physical activity and this investigation and I understand I will be taking part at my own risk.

Participant’s name & signature:__________________________________Date:

Investigator’s name & signature:_________________________________Date:

Appendix C

Participant Information Sheet and Ethical Approval - *First Experiment*

Effect of Physical and Mental Workload Interactions on Visual Attentional Resources

You will participate in the research study *"EFFECT OF PHYSICAL AND MENTAL WORKLOAD INTERACTIONS ON VISUAL ATTENTIONAL RESOURCES PERFORMANCE"* with Abdulrahman Basahel PhD researcher (investigator), under supervision of Dr. Mark Young (School of Engineering & Design, Tower A, Room TA011, (m.young@brunel.ac.uk,Tel: 01895266527) and Dr.Marco Ajovalaist (School of Engineering and Design, Tower A, Room TA015,), (marco.ajovalasit@brunel.ac.uk Tel: 01895267134), and to be conducted at Brunel University.

The aims of this study are to determine the effect of physical and mental workload interaction at different levels of visual arithmetic and spatial figures tasks on individual attentional resources performance. Firstly, you will be asked to:

- Fill a health questionnaire then, you will be asked to:

- To visit the laboratory two times: first, you will come to warm-up and measure the maximum physical workload (it will be take max 10 min). Second visit, you will perform the experiment, this will be take no more than 2.5 hours.

- Perform physical exercise under three different levels.
- Solve visual arithmetic tasks under three different levels or,.
- Complete spatial figure tasks under three different levels.
- Fill out a short set of rating scales for physical and mental workload.
- Finally you will get £25 for your time and effort.

The tasks will all be completed on a computer and bicycle-ergometer, and your performance recorded automatically by the software. Your performance will not be judged – we are more interested in the effects of the task than how 'good' you are, so please just try to do the best you can. We would also like to record your heart rate using a sports-type heart rate monitor, blood pressure using digital monitoring and oxygenation changes in the brain by using Near-Infrared Spectroscopy (NIRS) , which are simple and safe to use – the experimenter will explain it to you and give you privacy to put heart rate monitor on, as it has to go straight on your chest.

All data will remain anonymous and confidential and just used for the purposes of this study. Your participation is voluntary and you have the right to withdraw from the study at any time, or to have your data withdrawn at a later date if you so wish.

If you have any questions about the study, please ask the experimenter, and if you would like further information at a later date or are interested in the results of the study, please contact Abdulrahman at Abdulrahman.Basahel@brunel.ac.uk, Phone: 07513 046051.

Who should you contact if you wish to make a complaint about the study? You can contact the Chair of the University Research Ethics Committee, Dr. David Anderson-Ford,(David. Anderson-Ford@brunel.ac.uk).

This research project has been approved by the Brunel University Ethics Committee.

I have read and understood these instructions, and I have had the opportunity to ask questions. I understand my participation is voluntary and I have the right to withdraw at any time. I have been offered a copy of this consent form.

Print name: ____

Participant’s Signature_________________,Date __________________

Ethical Approval – *First Experiment*

Brunel
UNIVERSITY
WEST LONDON

University Research Ethics Committee

08 July 2010

Letter of Approval

Proposer: **Abdulrahman Basahel**
School of Engineering and Design

Title: **Effects of Physical and Mental Workload Interaction on Human Attentional Resources Performance**

Dear Mr. Basahel,

The University Research Ethics Committee has considered the amendments recently submitted by you in response to the Committee's earlier review of the above application.

The Chair, acting under delegated authority, is satisfied that the amendments accord with the decision of the Committee and has agreed that there is no objection on ethical grounds to the proposed study.

Any changes to the protocol contained in your application, and any unforseen ethical issues which arise during the project, must be notified to the Committee.

The Committee would appreciate a report on the project following its completion. This should include some indication of the success of the project, whether any adverse events occurred, and whether any participants withdrew from the research.

Kind regards,

D. Anderson - Ford

David Anderson-Ford
Chair, Research Ethics Committee
Brunel University

Appendix D

Participant Information Sheet and Ethical Approval - *Second Experiment*

Influence of Physical and Mental Workload Interactions on Auditory Attentional Resources Performance

You will participate in the research study *"Influence of Physical and Mental Workload Interactions on Auditory Attentional Resources Performance"* with Abdulrahman Basahel PhD researcher (investigator), under supervision of Dr. Mark Young (School of Engineering & Design, Tower A, Room TA011, (m.young@brunel.ac.uk,Tel: 01895266527) and Dr.Marco Ajovalaist (School of Engineering and Design, Tower A, Room TA015,), (marco.ajovalasit@brunel.ac.uk Tel: 01895267134), and to be conducted at Brunel University.

The aims of this study are to determine the effect of physical and mental workload interaction at different levels of visual arithmetic and spatial figures tasks on individual attentional resources performance. Firstly, you will be asked to:

- Fill a health questionnaire then, you will be asked to:

- To visit the laboratory two times: first, you will come to warm-up and measure the maximum physical workload (it will be take max 10 min). Second visit, you will perform the experiment, this will be take no more than 2.5 hours.

- Perform physical exercise under three different levels.
- Solve auditory arithmetic tasks under three different levels or,.
- Perform tone localization tasks under three different levels.
- Fill out a short set of rating scales for physical and mental workload.
- Finally you will get £25 for your time and effort.

The tasks will all be completed on a computer and bicycle-ergometer, and your performance recorded automatically by the software. Your performance will not be judged – we are more interested in the effects of the task than how 'good' you are, so please just try to do the best you can. We would also like to record your heart rate using a sports-type heart rate monitor, blood pressure using digital monitoring and oxygenation changes in the brain by using Near-Infrared Spectroscopy (NIRS) , which are simple and safe to use – the experimenter will explain it to you and give you privacy to put heart rate monitor on, as it has to go straight on your chest.

All data will remain anonymous and confidential and just used for the purposes of this study. Your participation is voluntary and you have the right to withdraw from the study at any time, or to have your data withdrawn at a later date if you so wish.

If you have any questions about the study, please ask the experimenter, and if you would like further information at a later date or are interested in the results of the study, please contact Abdulrahman at Abdulrahman.Basahel@brunel.ac.uk, Phone: 07513 046051.

Who should you contact if you wish to make a complaint about the study? You can contact the Chair of the University Research Ethics Committee, Dr. David Anderson-Ford,(David. Anderson-Ford@brunel.ac.uk).

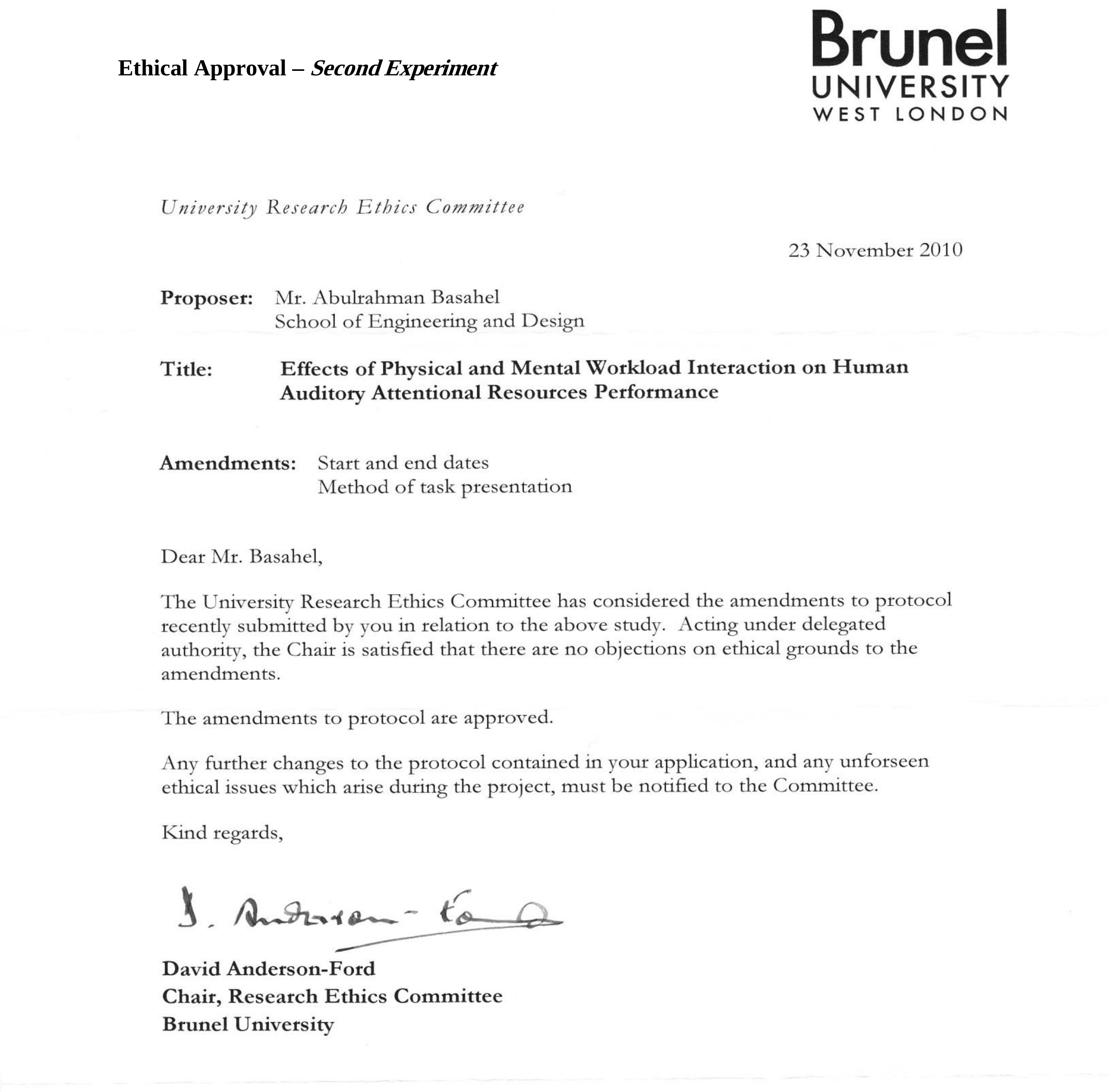
This research project has been approved by the Brunel University Ethics Committee.

I have read and understood these instructions, and I have had the opportunity to ask questions. I understand my participation is voluntary and I have the right to withdraw at any time. I have been offered a copy of this consent form.

Print name: ____

Participant's Signature ______________________,Date_____________________

Ethical Approval – *Second Experiment*



Brunel
UNIVERSITY
WEST LONDON

University Research Ethics Committee

23 November 2010

Proposer: Mr. Abulrahman Basahel
School of Engineering and Design

Title: **Effects of Physical and Mental Workload Interaction on Human Auditory Attentional Resources Performance**

Amendments: Start and end dates
Method of task presentation

Dear Mr. Basahel,

The University Research Ethics Committee has considered the amendments to protocol recently submitted by you in relation to the above study. Acting under delegated authority, the Chair is satisfied that there are no objections on ethical grounds to the amendments.

The amendments to protocol are approved.

Any further changes to the protocol contained in your application, and any unforseen ethical issues which arise during the project, must be notified to the Committee.

Kind regards,

D. Anderson-Ford

David Anderson-Ford
Chair, Research Ethics Committee
Brunel University

Appendix E

Participant Information Sheet and Ethical Approval - *Third Experiment*

Effects of Physical Lifting Workload and Mental Workload Interaction on Auditory Task Performance

You have been asked to participate in the research study *"Effects of Physical and Mental Workload Interaction on Auditory Task Performance"* with Abdulrahman Basahel PhD researcher (investigator), under supervision of Dr. Mark Young (School of Engineering & Design, Tower A, Room TA011, (m.young@brunel.ac.uk,Tel: 01895266527) and Dr.Marco Ajovalaist (School of Engineering and Design, Tower A, Room TA015,), (marco.ajovalasit@brunel.ac.uk Tel: 01895267134), to be conducted at Brunel University.

The aims of this study are to determine the effect of physical and mental workload interaction at different levels of difficulty on individual performance. You will be asked to:

- Complete a health questionnaire then
- Visit the laboratory one time to perform the experiment, this will be take no more than 2.5 hours.
- Perform a physical task (box lifting) under three different levels of difficulty, meanwhile
    - Solve arithmetic tasks which will be presented verbally under three levels of difficulty or
    - Complete an auditory localization task presented via speakers in the laboratory, again under three different levels of difficulty.
    - There are nine conditions in total – 3 levels of difficulty for the physical task, multiplied by three levels of difficulty for the mental task. Each condition lasts for six minutes.
- Fill out a short set of rating scales for physical and mental workload after each task.
- Finally you will receive £25 for your time and effort.

The mental tasks will all be completed verbally and the experimenter will be recorded the response on the computer, and it will be saved in the software. Your performance will not be judged – we are more interested in the effects of the task than how 'good' you are, so please just try to do the best you can. We would also like to record your heart rate using a sports-type heart rate monitor, blood pressure using digital monitoring and oxygenation changes in the brain by using specialist electrodes, which are all simple and safe to use – the experimenter will explain it to you and give you privacy to put heart rate monitor on, as it has to go straight on your chest.

All data will remain anonymous and confidential and just used for the purposes of this study. Your participation is voluntary and you have the right to withdraw from the study at any time, or to have your data withdrawn at a later date if you so wish.

If you have any questions about the study, please ask the experimenter, and if you would like further information at a later date or are interested in the results of the study, please contact Abdulrahman at Abdulrahman.Basahel@brunel.ac.uk, Phone: 07513 046051.

Who should you contact if you wish to make a complaint about the study? You can contact the Chair of the University Research Ethics Committee, Dr. David Anderson-Ford,(David. Anderson-Ford@brunel.ac.uk).

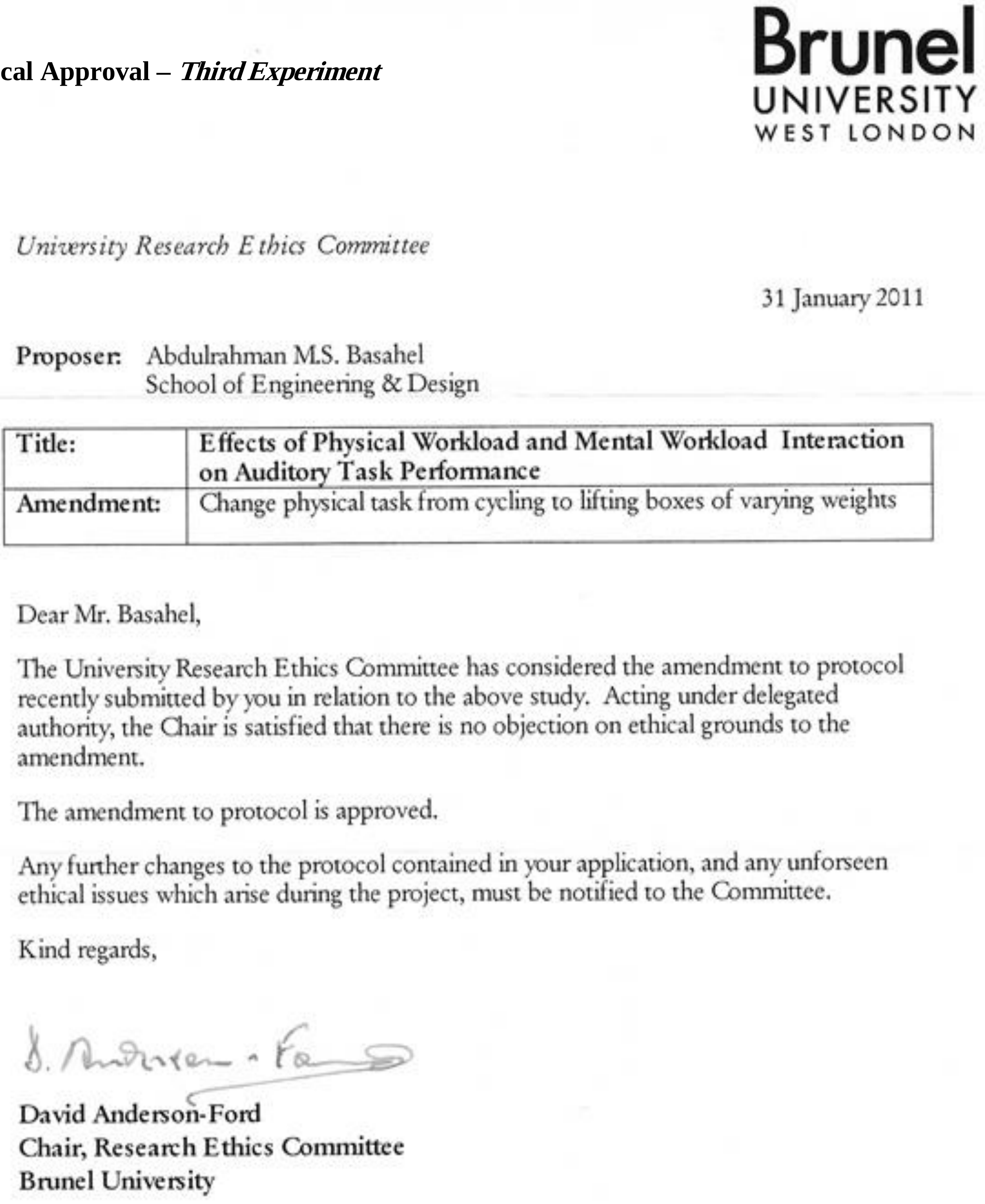
This research project has been approved by the Brunel University Ethics Committee.

I have read and understood these instructions, and I have had the opportunity to ask questions. I understand my participation is voluntary and I have the right to withdraw at any time. I have been offered a copy of this consent form.

Print name: ____

Participant's Signature ______________________,Date ______________________

Ethical Approval – *Third Experiment*



Brunel
UNIVERSITY
WEST LONDON

University Research Ethics Committee

31 January 2011

Proposer: Abdulrahman M.S. Basahel
School of Engineering & Design

Title:	**Effects of Physical Workload and Mental Workload Interaction on Auditory Task Performance**
Amendment:	Change physical task from cycling to lifting boxes of varying weights

Dear Mr. Basahel,

The University Research Ethics Committee has considered the amendment to protocol recently submitted by you in relation to the above study. Acting under delegated authority, the Chair is satisfied that there is no objection on ethical grounds to the amendment.

The amendment to protocol is approved.

Any further changes to the protocol contained in your application, and any unforseen ethical issues which arise during the project, must be notified to the Committee.

Kind regards,

D. Anderson-Ford

David Anderson-Ford
Chair, Research Ethics Committee
Brunel University

Appendix F

Informed Consent Form – *Across all experiments*

The participant should complete the whole of this sheet himself

Please tick the appropriate box

	YES	NO
Have you read the Research Participant Information Sheet?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Have you received satisfactory answers to all your questions?	☐	☐
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?	☐	☐
Do you understand that you are free to withdraw from the study:		
- at any time	☐	☐
- without having to give a reason for withdrawing?	☐	☐
- *(where relevant)* without affecting your future employment as a member of staff of the University or your progression or assessment as a student of the University.	☐	☐
Do you agree to take part in this study?	☐	☐

Signature of Research Participant:

Date:

Name in capitals:

Witness statement
I am satisfied that the above-named has given informed consent.
Witnessed by:
Date:
Name in capitals:

This study is being conducted as part of the PhD research of Abdulrahman Basahel,(Abdulrahman.Basahel@brunel.ac.uk, Phone: 07513 046051) and is supervised by Dr. Mark Young (School of Engineering & Design, Tower A, Room TA011, (m.young@brunel.ac.uk,Tel: 01895266527) and Dr.Marco Ajovalaist (School of Engineering and Design, Tower A, Room TA015,), (marco.ajovalasit@brunel.ac.uk Tel: 01895267134).

Appendix G

NASA-TLX Mental Workload Rating Scale

Please place an "X" along each scale at the point that best indicates your experience with the display configuration.

Mental Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low ____________________ High

Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low ____________________ High

Temporal Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low ____________________ High

Performance: How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Low ____________________ High

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low ____________________ High

Frustration: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low ____________________ High

Appendix H

Borg-CR10 Scale (Borg, 1998)

Please place a circle along scale at the point that best indicates your experience with the physical load level.

0	**Nothing at all**	**“No P”**
0.3		
0.5	**Extremely weak**	**Just noticeable**
1	**Very weak**	
1.5		
2	**Weak Light**	
2.5		
3	**Moderate**	
4		
5	**Strong Heavy**	
6		
7	**Very strong**	
8		
9		
10	**Extremely strong “Max P”**	
11		
ϟ		
●	**Absolute maximum**	**Highest possible**

Appendix H

Borg-RPE Scale (Borg, 1998)

Please place a circle along scale at the point that best indicates your experience with the physical load level.

6	**No exertion at all**
7	**Extremely light**
8	
9	**Very light**
10	
11	**Light**
12	
13	**Somewhat hard**
14	
15	**Hard (heavy)**
16	
17	**Very hard**
18	
19	**Extremely hard**
20	**Maximal exertion**

Appendix I

- Summary of descriptive statistics of measures (means ±SD) across nine physical and mental workload interactions conditions in cycling vs. visual arithmetic task (First experiment)

	Physical Workload								
	Low (20% of max. workload capacity)			Medium (50%)			High (80%)		
	Mental Workload								
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Performance Variables									
− Accuracy (%)	(91.1 ± 5.4)	(88.0 ± 6.1)	(78.2 ± 6.4)	(96.0 ± 5.2)	(79.3 ± 5.3)	(67.4± 5.9)	(81.2 ± 6.8)	(73.0 ± 4.6)	(57.7 ± 5.9)
− Time of task (sec)	(48.7 ± 9.6)	(66.4 ± 8.2)	(112.2 ± 10.4)	(39.8 ± 7.1)	(58.8 ± 8.2)	(150.0 ± 9.1)	(72.3 ± 7.9)	(150.5 ± 6.6)	(188.2 ± 8.8)
Physiological Variables									
−HR (b/min)	(105.1 ± 7.3)	(112.80 ± 9.8)	(120.93 ± 7.3)	(113.2 ± 11.2)	(129.40 ± 9.1)	(140.73 ± 8.4)	(134.7 ± 7.1)	(147.20 ± 8.2)	(153.52 ± 10.4)
−HRV (ms)	(664.7 ± 88.5)	(561.3 ± 70.2)	(457.7 ± 91.4)	(854.3 ± 100.1)	(712.9 ± 86.9)	(618.7 ± 101.4)	(1184.4 ± 97.6)	(997.4 ± 102.6)	(838.9 ± 100.3)
−MBP (mmHg)	(87.2 ± 7.5)	(92.6 ± 5.3)	(97.3 ± 5.9)	(95.4 ± 7.2)	(101.4 ± 4.9)	(110.2 ± 6.1)	(103.60 ± 7.3)	(112.8 ± 6.2)	(121.4 ± 5.6)
Brain Activity Variable									
− rSO2 (%)	(66.8 ± 2.3)	(75.6 ± 1.9)	(80.60 ± 2.1)	(62.2 ± 3.3)	(70.3 ± 2.1)	(75.1 ± 3.8)	(58.4 ± 2.6)	(68.6 ± 1.5)	(73.9 ± 2.7)
Borg Scales									
−CR-10	(1.21 ± 1.6)	(1.22 ± 2.1)	(1.21 ± 1.9)	(3.30 ± 1.2)	(3.27 ± 0.9)	(3.27 ± 2.2)	(6.63 ± 1.4)	(6.73 ± 1.6)	(6.71 ± 1.3)
−RPE	(8.73 ± 1.1)	(8.69 ± 1.6)	(8.70 ± 1.9)	(13.27 ± 2.2)	(13.33 ± 1.5)	(13.29 ± 1.8)	(16.91 ± 1.09)	(16.87 ± 2.3)	(16.94 ± 1.7)
Overall-NASA-TLX	(13.3 ± 4.5)	(30.6 ± 7.2)	(55.6 ± 9.2)	(32.4 ± 4.7)	(47.9 ± 6.1)	(66.8 ± 10.1)	(51.8 ± 6.6)	(65.4 ± 5.9)	(83.7 ± 8.4)

- Summary of descriptive statistics of measures (means ±SD) across nine physical and mental workload interactions conditions in cycling vs. visual spatial figures task (First experiment).

	Physical Workload								
	Low (20% of max. workload capacity)			Medium (50%)			High (80%)		
	Mental Workload								
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Performance Variables									
− Accuracy (%)	(90.0 ± 5.1)	(86.5 ± 4.8)	(75.4 ± 6.1)	(94.0 ± 5.8)	(77.1 ± 4.2)	(65.2± 6.3)	(79.4 ± 6.6)	(72.0 ± 5.4)	(55.4 ± 4.1)
− Time of task (sec)	(50.2 ± 7.1)	(70.2 ± 8.6)	(118.9 ± 9.4)	(44.1 ± 6.3)	(60.8 ± 9.8)	(154.2 ± 10.9)	(74.8 ± 8.1)	(159.2 ± 6.2)	(198.9 ± 6.5)
Physiological Variables									
−HR (b/min)	(106.8 ± 8.2)	(115.3 ± 7.1)	(123.4 ± 10.1)	(120.1 ± 7.5)	(131.6 ± 8.3)	(149.3 ± 9.1)	(139.2 ± 10.4)	(151.7 ± 7.8)	(167.9 ± 8.9)
−HRV (ms)	(645.8 ± 66.1)	(550.8 ± 72.4)	(457.7 ± 79.8)	(826.6 ± 81.4)	(705.1± 59.7)	(618.7 ± 73.6)	(1098.0 ± 64.7)	(868.7 ± 71.0)	(838.9 ± 79.9)
−MBP (mmHg)	(90.1 ± 5.3)	(94.2 ± 4.1)	(98.9 ± 6.7)	(95.4 ± 5.6)	(103.7 ± 7.2)	(112.4 ± 5.3)	(105.2 ± 6.9)	(118.6 ± 6.8)	(126.0 ± 5.4)
Brain Activity Variable									
− rSO2 (%)	(67.2 ± 1.8)	(76.8 ± 1.2)	(85.2 ± 3.1)	(63.8 ± 2.4)	(72.4 ± 2.6)	(78.4 ± 1.9)	(58.9 ± 3.2)	(69.2 ± 1.7)	(76.6 ± 1.8)
Borg Scales									
−CR-10	(1.13 ± 1.2)	(1.27 ± 1.8)	(1.33 ± 1.4)	(3.40 ± 2.6)	(3.50 ± 1.3)	(3.43 ± 2.7)	(6.63 ± 1.8)	(6.73 ± 2.1)	(6.71 ± 1.9)
−RPE	(8.83 ± 1.6)	(8.93 ± 2.6)	(8.89 ± 2.3)	(13.40 ± 2.4)	(13.44 ± 1.1)	(13.47 ± 1.4)	(17.10 ± 2.4)	(17.19 ± 1.1)	(17.13 ± 1.4)
Overall-NASA-TLX	(14.6 ± 5.1)	(36.5 ± 6.4)	(56.9 ± 8.1)	(32.6 ± 5.2)	(49.4 ± 7.7	(73.6 ± 8.7)	(52.6 ± 7.9)	(70.1 ± 8.2)	(89.8 ± 5.5)

- Summary of descriptive statistics of measures (means ±SD) across nine physical and mental workload interactions conditions in cycling vs. auditory arithmetic task (Second experiment).

	Physical Workload								
	Low (20% of max. workload capacity)			Medium (50%)			High (80%)		
	Mental Workload								
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Performance Variables									
− Accuracy (%)	(85.4 ± 6.4)	(78.6 ± 5.3)	(68.3 ± 4.5)	(89.2 ± 6.2)	(71.0 ± 6.4)	(60.9± 5.4)	(69.8 ± 5.7)	(56.7 ± 4.9)	(47.6 ± 5.8)
− Time of task (sec)	(53.5 ± 6.6)	(69.4 ± 9.8)	(140.4 ± 10.2)	(47.4 ± 9.1)	(111.2 ± 6.1)	(181.8 ± 5.4)	(107.1 ± 7.2)	(175.6 ± 5.8)	(226.2 ± 6.3)
Physiological Variables									
−HR (b/min)	(113.2 ± 10.2)	(118.9 ± 9.3)	(125.7 ± 7.5)	(130.4 ± 8.2)	(136.2 ± 6.1)	(142.5 ± 7.7)	(145.8 ± 8.5)	(156.4 ± 6.2)	(168.2 ± 9.7)
−HRV (ms)	(730.3 ± 72.6)	(518.1 ± 85.1)	(208.5 ± 68.3)	(900.3 ± 72.8)	(676.3± 87.1)	(498.9 ± 80.4)	(1124.8 ± 74.4)	(839.7 ± 86.4)	(636.8 ± 67.3)
−MBP (mmHg)	(89.7 ± 7.1)	(95.9 ± 5.4)	(109.4 ± 9.7)	(101.9 ± 8.2)	(108.8 ± 9.6)	(119.1 ± 6.6)	(110.8 ± 5.9)	(119.4 ± 4.8)	(126.7 ± 7.6)
Brain Activity Variable									
− rSO2 (%)	(68.4 ± 1.1)	(79.3 ± 1.8)	(87.6 ± 2.7)	(62.5 ± 2.1)	(73.6 ± 1.9)	(80.1 ± 3.4)	(57.1 ± 1.5)	(67.6 ± 1.3)	(78.9 ± 2.4)
Borg Scales									
−CR-10	(1.51 ± 2.7)	(1.48 ± 2.1)	(1.46 ± 1.0)	(3.47 ± 2.3)	(3.52 ± 1.9)	(3.55 ± 1.2)	(7.0 ± 2.9)	(7.11 ± 3.1)	(7.13 ± 2.8)
−RPE	(8.32 ± 1.8)	(8.27 ± 1.3)	(8.30 ± 1.8)	(13.70 ± 3.1)	(13.74 ± 1.6)	(13.71 ± 1.2)	(17.67 ± 2.1)	(17.54 ± 2.6)	(17.57 ± 1.3)
Overall-NASA-TLX	(10.8 ± 7.2)	(31.8 ± 5.9)	(58.2 ± 6.3)	(34.2 ± 5.9)	(49.7 ± 8.1)	(76.4 ± 7.2)	(53.4 ± 6.6)	(67.8 ± 5.9)	(94.6 ± 7.3)

- Summary of descriptive statistics of measures (means ±SD) across nine physical and mental workload interactions conditions in cycling vs. tone localisation task (Second experiment).

	Physical Workload								
	Low (20% of max. workload capacity)			Medium (50%)			High (80%)		
	Mental Workload								
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Performance Variables									
− Accuracy (%)	(86.1 ± 4.8)	(79.1 ± 4.1)	(70.9 ± 6.9)	(92.8 ± 5.1)	(72.7 ± 5.2)	(60.93± 4.6)	(72.7 ± 6.1)	(58.9 ± 5.7)	(51.0 ± 5.0)
− Time of task (sec)	(53.22 ± 8.3)	(66.8 ± 5.3)	(139.2 ± 6.8)	(42.9 ± 7.7)	(95.9 ± 9.8)	(163.6 ± 9.1)	(106.0 ± 7.2)	(152.5 ± 7.1)	(201.4 ± 6.8)
Physiological Variables									
−HR (b/min)	(112.7 ± 13.8)	(116.6 ± 11.1)	(124.6 ± 8.1)	(129.0 ± 9.4)	(135.7 ± 7.2)	(141.0 ± 11.8)	(144.1 ± 6.9)	(152.7 ± 9.3)	(160.1 ± 8.4)
−HRV (ms)	(739.8 ± 70.9)	(522.4 ± 68.3)	(212.9 ± 86.6)	(924.0 ± 74.1)	(683.6± 81.6)	(531.1 ± 88.1)	(1179.2 ± 82.9)	(989.3 ± 72.9)	(742.6 ± 70.4)
−MBP (mmHg)	(88.5 ± 8.3)	(94.3 ± 6.7)	(108.6 ± 5.2)	(100.0 ± 10.1)	(106.9 ± 6.9)	(113.8 ± 7.5)	(109.8 ± 8.0)	(115.0 ± 6.6)	(121.1 ± 6.3)
Brain Activity Variable									
− rSO2 (%)	(68.0 ± 1.6)	(79.04 ± 3.1)	(82.4 ± 1.1)	(61.9 ± 1.8)	(73.2 ± 2.2)	(76.2 ± 2.3)	(56.8 ± 2.6)	(64.1 ± 2.1)	(74.5 ± 1.7)
Borg Scales									
−CR-10	(1.55 ± 1.3)	(1.46 ± 1.6)	(1.49 ± 2.4)	(3.53 ± 1.6)	(3.50 ± 1.3)	(3.54 ± 2.6)	(7.1 ± 1.4)	(7.08 ± 2.3)	(7.18 ± 1.5)
−RPE	(8.30 ± 2.1)	(8.26 ± 1.8)	(8.29 ± 1.0)	(13.69 ± 1.7)	(13.72 ± 2.4)	(13.72 ± 2.2)	(17.63 ± 1.8)	(17.56 ± 1.9)	(17.54 ± 2.0)
Overall-NASA-TLX	(8.6 ± 6.1)	(30.9 ± 7.2)	(50.5 ± 7.9)	(33.6 ± 6.7)	(46.2 ± 8.8)	(70.6 ± 6.6)	(52.6 ± 9.1)	(65.3 ± 6.0)	(85.2 ± 6.8)

- Summary of descriptive statistics of measures (means ±SD) across nine physical and mental workload interactions conditions in lifting box task vs. auditory arithmetic task (Third experiment).

	Physical Workload								
	Low (8% of body mass)			Medium (14%)			High (20%)		
	Mental Workload								
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Performance Variables									
− Accuracy (%)	(88.3 ± 8.1)	(81.1 ± 4.9)	(74.0 ± 6.8)	(91.2 ± 8.0)	(73.6 ± 5.2)	(64.7± 5.6)	(73.8 ± 5.9)	(64.5 ± 6.4)	(56.7 ± 7.3)
− Time of task (sec)	(73.6 ± 7.2)	(69.4 ± 8.4)	(141.8 ± 7.4)	(66.4 ± 5.3)	(130.5 ± 5.8)	(184.7 ± 7.9)	(103.2 ± 5.6)	(175.6 ± 7.4)	(236.4 ± 5.6)
Physiological Variables									
−HR (b/min)	(109.2 ± 8.1)	(117.1 ± 10.8)	(124.2 ± 8.9)	(126.8 ± 10.2)	(134.8 ± 6.1)	(138.5 ± 8.3)	(142.2 ± 9.2)	(150.1 ± 9.1)	(167.5 ± 7.8)
−HRV (ms)	(789.6 ± 75.8)	(546.3 ± 84.9)	(387.3 ± 68.6)	(968.1 ± 69.1)	(687.7± 86.3)	(564.2 ± 77.9)	(1184.4 ± 77.1)	(904.9 ± 71.8)	(691.4 ± 65.7)
−MBP (mmHg)	(86.2 ± 6.8)	(92.6 ± 6.0)	(99.8 ± 5.1)	(98.8 ± 6.1)	(104.5 ± 7.9)	(114.2 ± 5.2)	(108.7 ± 6.1)	(116.4 ± 6.3)	(126.2 ± 7.2)
Brain Activity Variable									
− rSO2 (%)	(68.0 ± 2.3)	(75.4 ± 2.4)	(88.6 ± 1.4)	(63.0 ± 1.2)	(69.7 ± 2.3)	(77.3 ± 2.6)	(56.6 ± 2.5)	(63.9 ± 2.4)	(76.8 ± 1.7)
Borg Scales									
−CR-10	(1.53 ± 1.4)	(1.31 ± 1.6)	(1.47 ± 2.3)	(3.77 ± 3.2)	(3.67 ± 1.3)	(3.80 ± 1.9)	(7.64 ± 2.7)	(7.70 ± 2.6)	(8.02 ± 3.2)
−RPE	(8.76 ± 1.1)	(8.58 ± 2.6)	(8.67 ± 1.4)	(14.04 ± 1.7)	(13.70 ± 2.9)	(13.76 ± 3.1)	(17.68 ± 2.4)	(17.91 ± 1.8)	(18.12 ± 2.4)
Overall-NASA-TLX	(8.9 ± 6.1)	(33.2 ± 6.4)	(50.0 ± 8.1)	(34.9 ± 6.2)	(48.3 ± 7.7)	(74.3 ± 5.6)	(54.2 ± 6.1)	(68.6 ± 6.4)	(90.9 ± 5.9)

- Summary of descriptive statistics of measures (means ±SD) across nine physical and mental workload interactions conditions in lifting box task vs. tone localisation task (Third experiment).

	Physical Workload								
	Low (8% of body mass)			Medium (14%)			High (20%)		
	Mental Workload								
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Performance Variables									
− Accuracy (%)	(88.5 ± 5.3)	(82.3 ± 6.2)	(74.8 ± 6.7)	(93.3 ± 5.3)	(74.0 ± 7.1)	(67.4± 6.8)	(74.5 ± 8.1)	(66.3 ± 6.0)	(58.4 ± 6.7)
− Time of task (sec)	(72.5 ± 5.6)	(67.7 ± 6.8)	(136.7 ± 9.2)	(65.8 ± 6.9)	(122.4 ± 7.1)	(168.2 ± 6.4)	(100.8 ± 6.2)	(161.3 ± 5.8)	(204.9 ± 7.3)
Physiological Variables									
−HR (b/min)	(106.8 ± 7.4)	(114.4 ± 9.8)	(123.4 ± 8.6)	(125.2 ± 7.8)	(133.6 ± 7.2)	(138.2 ± 9.1)	(141.4 ± 10.2)	(149.8 ± 6.7)	(157.0 ± 8.3)
−HRV (ms)	(825.2 ± 80.4)	(624.4 ± 85.6)	(461.7 ± 74.4)	(1042.6 ± 86.1)	(713.8± 68.6)	(608.2 ± 84.9)	(1202.1 ± 78.5)	(1021.2 ± 76.2)	(822.3 ± 84.2)
−MBP (mmHg)	(85.6 ± 6.6)	(88.3 ± 5.9)	(98.9 ± 5.4)	(97.9 ± 7.2)	(103.6 ± 8.3)	(112.8 ± 6.4)	(107.6 ± 6.1)	(114.2 ± 5.9)	(123.3 ± 6.0)
Brain Activity Variable									
− rSO2 (%)	(67.3 ± 1.8)	(74.9 ± 3.2)	(84.0 ± 2.9)	(62.4 ± 1.8)	(67.6 ± 2.8)	(73.1 ± 3.4)	(56.1 ± 1.2)	(62.1 ± 1.9)	(71.9 ± 2.2)
Borg Scales									
−CR-10	(1.51 ± 1.8)	(1.37 ± 1.6)	(1.46 ± 2.1)	(3.34 ± 2.7)	(3.64 ± 2.3)	(3.91 ± 1.8)	(6.91 ± 1.5)	(7.65 ± 2.8)	(7.67 ± 2.1)
−RPE	(8.31 ± 2.4)	(8.76 ± 2.0)	(8.57 ± 3.1)	(13.80 ± 1.6)	(13.68 ± 2.9)	(13.60 ± 1.6)	(17.93 ± 1.9)	(17.71 ± 2.3)	(17.67 ± 1.8)
Overall-NASA-TLX	(7.8 ± 8.4)	(32.3 ± 6.2)	(47.6 ± 5.9)	(32.6 ± 6.2)	(47.2 ± 7.1)	(61.4 ± 9.1)	(51.8 ± 8.2)	(63.9 ± 6.4)	(80.0 ± 8.6)