Testing Hollnagel's Contextual Control Model: Assessing team behaviour in a human supervisory control task.

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This paper sets out to test the hypothetical COCOM model developed by Hollnagel (1993). Essentially, Hollnagel develops the argument that team behaviour should be analysed at a macro, rather than micro, level. He proposes four principal models of team activity: strategic, tactical, opportunistic, and scrambled. This modes of team behaviour vary in terms of the degree of forward planning (highest in the strategic mode) and reactivity to the environment (highest in the scrambled mode). He further hypothesises a linear progression through the modes from strategic to tactical to opportunistic to scrambled, depending upon context, and vice versa. To test the COCOM model, we placed teams of people in a simulated energy distribution system. Our results confirm Hollnagel's hypothesised model in two main ways. First, we show that the team behaviour could be categorised reliably into the four control modes and this provided a useful way of distinguishing between experimental conditions. Second, the progression between control modes conformed to the linear progression as predicted. This research provided the first independent test of the COCOM model and lends empirical support to the hypotheses.

KEYWORDS: Hollnagel, COCOM, Team behaviour, Human supervisory control

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INTRODUCTION

There is a tradition of research being conducted into control room operation, to enhance our understanding of the role of the human operators and learn about new ways of supporting those activities (Edwards & Lees, 1974). According to Kragt (1994) technological developments in process control have led to dramatic changes in the nature of work practices and behaviours. The first revolution was to automate parts of the process so that workers were able to supervise larger areas of plant. The second revolution was to centralise the controls and displays into a single control room, again enabling workers to supervise larger areas of plant. The third revolution was to put all the information at the workers fingertips via information technology, further reducing the personnel requirements. A review of research into human supervisory control reveals three distinct phases over the past three decades (Stanton, Ashleigh & Gale; 1997). Research in the 1970's may be characterised by interest in cognitive control (Edwards, & Lees 1974; Rasmussen, 1974). Interest in the individual shifted to interest in team structure and performance in the 1980's (e.g. Stammers & Hallam, 1985; Foushee & Helmreich, 1988). More recently, i.e. the 1990's, researchers have been focusing on human behaviour in context, e.g. Hollnagel's COtext and COntrol Model (COCOM: Hollnagel, 1993) and Stanton & Baber's Alarm Initiated Activities (AIA: Stanton & Baber, 1995). Zwaga & Hoonhout (1994) argue that traditionally the technological developments in supervisory control have been based upon the conception of the control room engineers task of 'operation-by-exception': control room engineers only intervening in the process when called to do so by the alarm system (Dallimonti, 1972). Zwaga & Hoonhout (1994) however, suggest that this concept is fundamentally flawed. By contrast, they propose, control room engineers behaviour is better characterised by a 'management-through-awareness' strategy: control room engineers are actively extracting information from their environment rather than passively reacting to alarms. The dichotomy of 'active extraction' and 'passive reception' were noted by Stanton & Baber (1995) in an analysis of alarm handling activities. A recent study of control rooms in the energy distribution industry, results found that in some situations, people were system driven, instead of taking control; albeit the aim was towards more pre-planned control (Stanton & Ashleigh, 2000). The dichotomy between reactive and proactive control is reinforced in the proposals for the COCOM model. Although procedural models have dominated explanations of human cognition for some time, there has more recently been a movement in human factors towards a more contextual approach in trying to model human behaviour. Hollnagel (1993) argues, operator control cannot be assumed to be as straightforward as the recursive use of Rasmussen's (1986) step-ladder model. He suggest that procedural models have become redundant as they fail to explain the flexibility and variety of the operator; nor do they take into account the dynamic environment in which human behaviour is carried conducted.

Hollnagel (1993) developed a Contextual Control approach to human behaviour, based on 'cognitive modules' rather than task goals (Bainbridge, 1991), and the context in which people performed their actions. This was similar to the concept of anticipatory control, such as trying to prevent an undesirable future events (Pew et al, 1981, cited in Hollnagel 1993), rather than merely a reactive control process. Hollnagel (1993) proposed that control is influenced by a number of factors namely; context, knowledge or experiences of the pre-conditions of previous actions, expectation of outcome and availability of resources. He emphasises that the "*essence of control is planning*" (p,168) and by planning, this automatically prescribes a certain number or sequence of competencies. He divided the competence factor into two separate parameters. 'The activity set' which are those *'ready actions that an operator is capable of carrying out and which are meaningful in the existing context'* (p164). Secondly are the *'template set'* that refer to the plans procedures, rules or heuristics, that an operator may use in order to guide the action taken. However, rather than control being a pre-determined sequence of events, it is a constructive operation where the operator actively decides which action to take according to the context of the situation together with his/her own level of competence. Although set patterns of behaviour maybe observed, Hollnagel points out that this is reflective of both the environment as well as the cognitive goal of the person, both of which contain variability. In the Contextual Control Model (COCOM), (as shown in figure 1), four proposed modes of control are:-

- *Scrambled Control* - is characterised by a completely unpredictable situation where the operator has no control and has to act in an unplanned manner, as a matter of urgency. An example of this may be where there is a sudden accident or emergency, where the operator is unfamiliar with the situation and/or lacks experience in what to do - the engineer's behaviour may be impulsive or even panicky. Consequently this is the mode where most errors occur.

- *Opportunistic Control* - is characterised by a chance action taken due to time, constraints and again lack of knowledge or expertise and an abnormal environmental state. An example of this may be in a situation where operators are driven by the perceptual dominance of system interface (alarms, lights, noise), and will revert to habitual heuristics, (Reason, 1990). In certain situations, opportunistic control may be used as a way of exploring a problem or situation and testing out alternative solutions, because of an unusual occurrence. This is referred to as *'Explorative Control'*.

- *Tactical Control* - is more characteristic of a pre-planned action, where the operator will use known rules and procedures to plan and carry out short term actions. Consequently, fewer errors will be made than in the previous modes, however the operator is still heavily driven by the immediacy of the situation, and therefore will still be influenced by the system interface.

- *Strategic Control* - is defined as the 'global view', where the operator concentrates on long term planning and higher level goals. In this mode, the operator will have evaluated the outcome more precisely, and considered the relationship between action and its pre-conditions; s/he will therefore have more overall control of the whole situation or task.

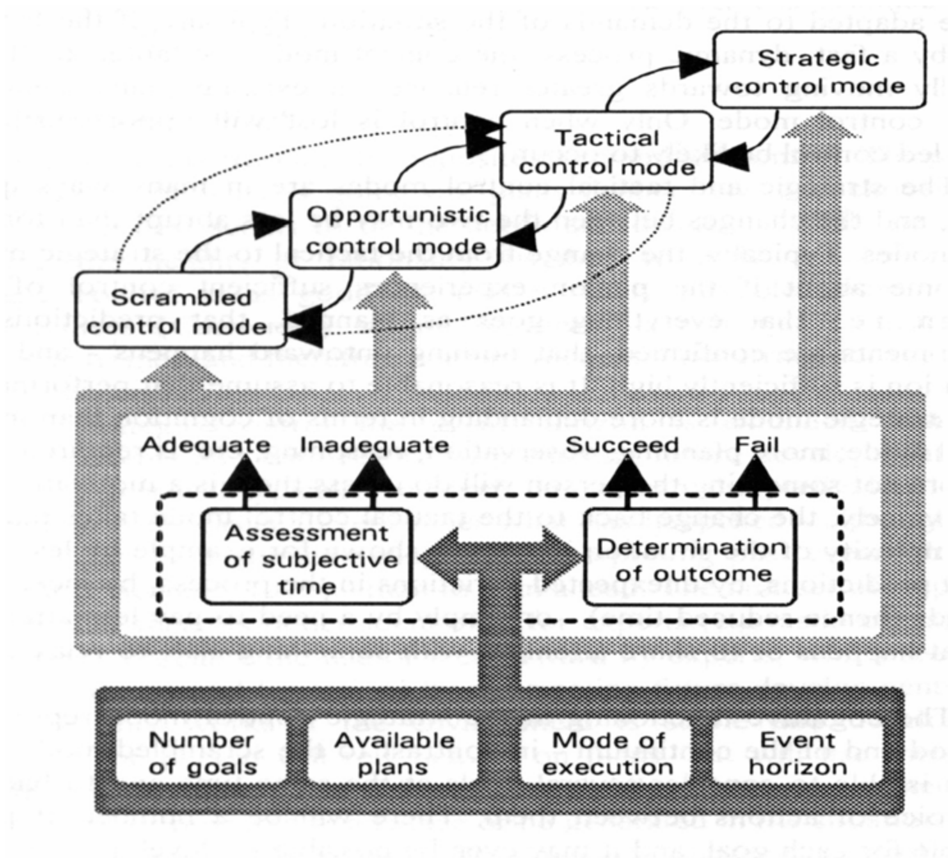

Figure 1. The internal structure of the COCOM. From (Hollnagel, Erik 1993), *Human Reliability Analysis: Context and control*, p192, Academic Press: London

Rather than a static sequence of control, this model depicts control as acting on a moving continuum; emphasising the dynamism of the environment and how operators necessarily have to quickly shift from one mode to the other. Degree of control therefore is a determined by a number varying interdependent factors. Hollnagel considers that availability of subjective time is a main function of control - briefly explained this means that as the operator perceives more time available so s/he gains more control of the task/situation. If someone who is already in a *scrambled mode* of control takes an action which is incorrect, his already perceived non-existent time slot, becomes even more reduced, and the goal becomes further removed, as the actual time diminishes and panic sets in. However if the action is correct, immediately the operator is nearer to achieving the goal, so the perception of available time increases and the degree of control moves up along the continuum. However this subjectivity is in turn dependent upon actual time available, rate of change process, competence of person, support or backup from organisation and the system interface.

According to Annett & Stanton (2000), the main design issues in contemporary team working research are the structure of the team, training of the team, and development of the human-machine interface. This paper proposes to address the first and third issues. Carletta et al (2000) present an optimistic picture for virtual team work. They suggest that a relatively modest level of technology can support collaborative working, despite the non co-location of people. They do point out however, that virtual team working may affect the dynamics of the team and practical issues, such as turn-taking in discussions, need to be resolved. This may require new ways of thinking about the design of interface technologies, to support collaborative decision making by team members who are no longer co-located. Two opposing themes for interface design are to either opt for a physical analogue of the real world or to opt for a goal-oriented, functional, abstraction of it (Rasmussen, 1996). Both of these design themes are investigated in the empirical study.

Theoretical contributions in Human Supervisory Control have largely centred around models of the human operators (Rasmussen, 1974; Stammers & Hallam, 1986; Hollnagel, 1993) and their interaction with automated systems (Bainbridge, 1983; Reason, 1990; Norman, 1990). This presents an interesting research paradigm in which to consider the degree of control, and sometimes lack of control, that human operators have over dynamic, complex, and closely coupled systems (Perrow, 1984). COCOM differentiates between control activity along the dimensions of criticality of decision making and time available for decisions to be made. This paper explores the relationship between control mode and system states to see if different interfaces and proximity of personnel provide control teams with greater opportunity for strategic control and less demand for scrambled control. We also intend to test the theoretical model, in particular to consider shifts between levels of control as it is hypothesised as sequential, albeit that there is some possibility to move directly from 'tactical' to 'scrambled' control and vice versa.

METHOD

The experimental method used in this study was as follows.

Participants

Participants used were a random sample of people from both academic and industrial backgrounds who had some interest in and/or engineering experience. There were 24 groups of 4 people used in the study, a total of 96 participants. Participants ages were from 19 to 55; a range of 36 years with the mean age being 26. The sample consisted of 74 males and 22 females, however when the participants were separated into the four different groups (e.g. virtual-distal, virtual-proximal, abstract-distal, abstract-proximal), no significant differences in distribution of gender were found. Fifty participants (52%) did not have actual engineering experience, although were undertaking an engineering based degree. The forty-six participants (48%) that were experienced ranged from 1 to 28 years, the mean being 2.9 years. No differences in the amount of experience were found between the four different groups. Of the sample, 73 participants were students (76%) and 23 (24%) in employment outside of academia. Of the student population over half were at postgraduate level.

Design

The study tested between factors using four different conditions, where six teams of four people were asked to perform a simulated task of balancing a gas-network system. They were either working together in the same location (proximal), or working in separate locations (distal), and using either a virtual or abstract interface (24 x 2 x 2). The dependent variable measures were time spent in each control mode by each team and transitions between control modes.

Equipment

Four networked PC's were used for the laboratory-based experiments. Each team member used a PC with either a virtual or abstract interface that represented a geographical area gas network, (e.g. North, South, East or West). Video cameras were used in each laboratory to record behavioural data of team members and allow visual communication across the distal condition. Telephones were used in the distal condition to enable communication amongst the team members. The software used to develop the two interfaces was *World Tool Kit*. The software package *Falcon* was adapted and used to form the link from the server to the four networked machines. Participants were also asked to complete a consent form.

Displays

VR User Interface is a 3D Graphic User Interface which provides an environment for operators to process the predict data to run system under certain constrains. There are four front user interfaces and they are topological identified but with different underlying specifications for each area network. Each area network has the following components: a regulator (shown as a representation of a valve with a control), consumers (shown as Field, Leigh, Ton and Industry), a holder (shown as a representation of a gas holder with a control panel) and pipes (shown as white pipes connecting system elements). Figure 2 shows one of the area network interfaces.

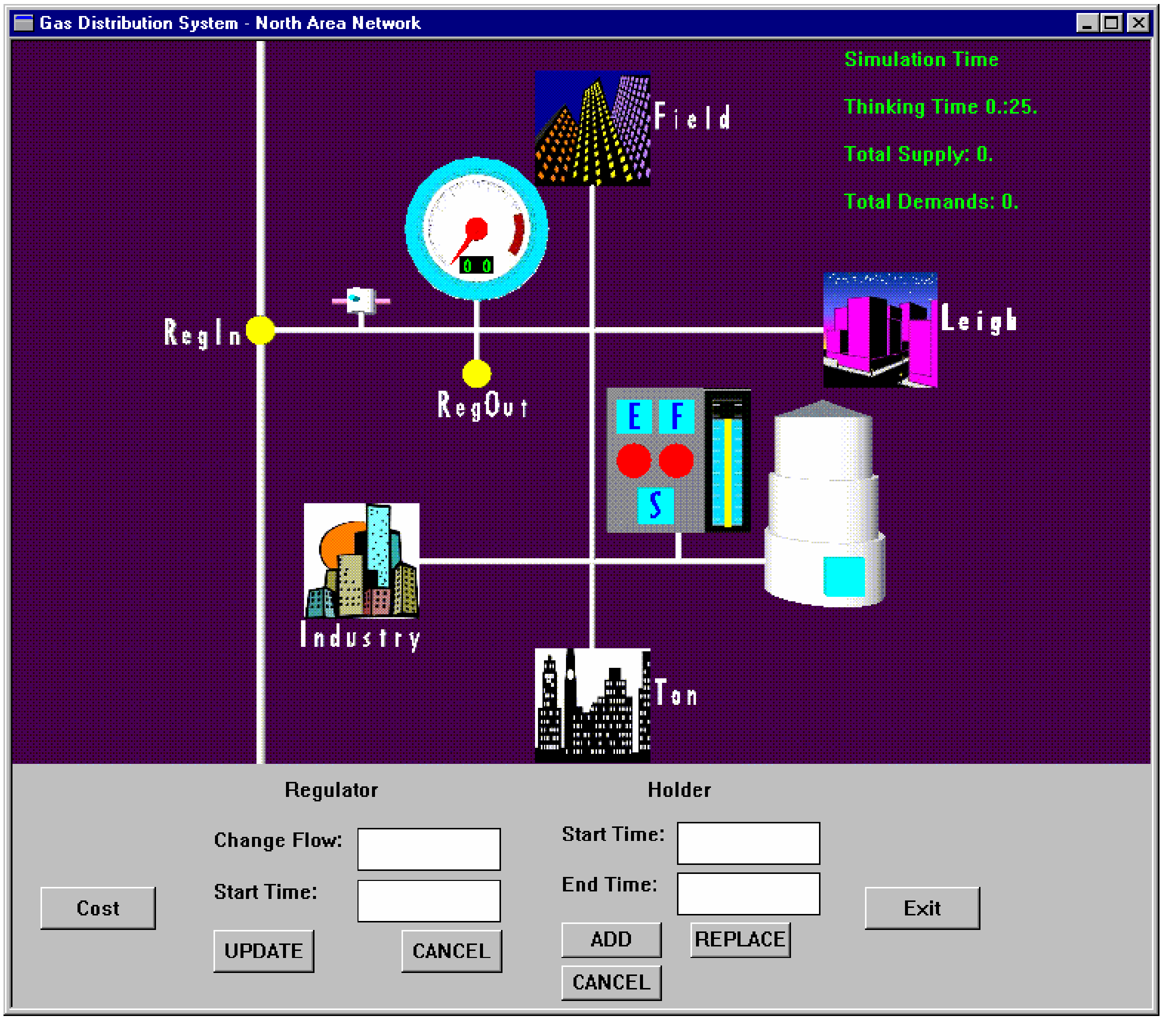

Figure 2 An example of the virtual user interface for North area.

In this Abstract Interface, we abstracted six parameters from the gas distribution system as six nodes to form a polygon. The shape of a polygon is changing while the state of a node is changing and each shape will present a state of the system either in balance or not. The node state can be changed by sending a command through a regulator or a holder. The six parameters abstracted from the gas distribution system were:

Balance: a difference between the total supply and the total demands plus a difference between the holder levels at beginning and end of the day. It could be a positive or a negative value and the optimal value is zero.

Holder Level at End of Day (EOD): the holder level at the end of day. The full capacity is 0.35MCM. Therefore a range of the value is [0, 0.35]. The optimal value is 0.35MCM at the position of full.

Minimum Pressure: an important parameter to be monitored which is required above 10bar. The optimal value is 10bar. If the value is less than 10bar, then it will run the system expensively.

Inlet flow-Demand: a difference between the total supply and the total demand. The value may be a positive or a negative. The optimal value is zero.

Pressure at EOD: the regulator output pressure at end of day. The maximum value is 38bar. The optimal value is 38bar.

Number of hours at 38bar: to measure how many hours the regulator output pressure is 38 bar over 24 hours. The optimal value is 1.

There are two hexagons in the abstract functional user interface screen (see figure 3). The green one with six equal sides represents the optimal performance that is provided to be a point-of-reference. The red hexagon shows the prediction and is subject to change over time.

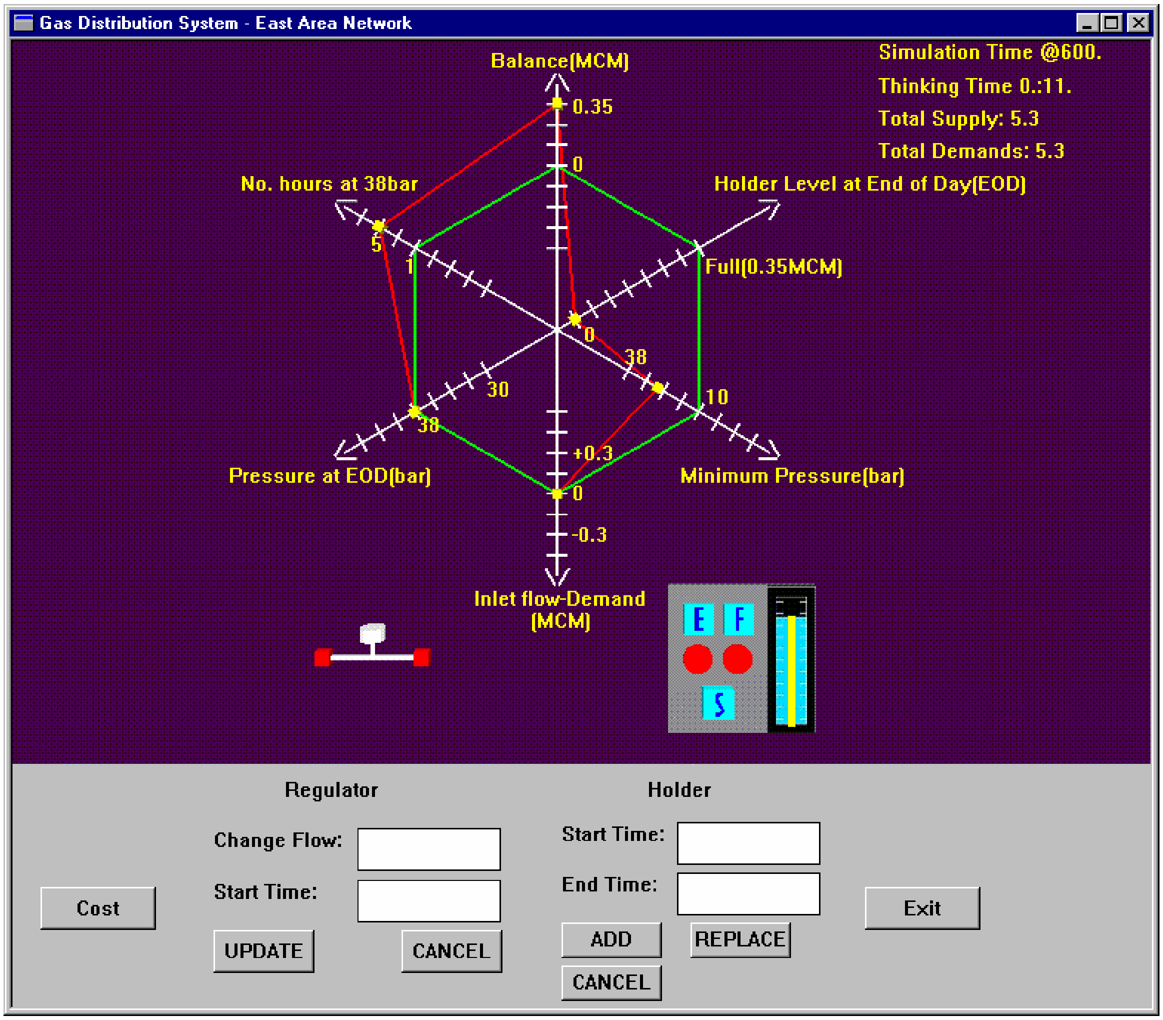

Figure 3. An example of the Abstract Functional user interface for East area

The two control points of the system and their associated data entry fields were kept the same in the two different interface environments. This was to ensure that any differences revealed would be due to the interface rather than the method of interaction. Theses two control points were via the regulator (i.e. the 'tap' in the pictures above), and the holder (the E, F, and S buttons on the control panel).

Experimental Task

The overall aim of the task was to operate a gas network so that all of the operational demands are met (e.g. the system imput-output remains in balance, system pressures are kept within tolerances and that operating costs are kept as low as possible). The network supplies four areas and each area is operated by an experimental participant. The gas is supplied to each area at a constant rate through a regulator. All areas have a working pressure range of between 10 bar and 38 bar.

The main objectives of the task were to:

- minimise overall flow-rate variation
- keep all pressures above 10 bar and below 38 bar
- operate system as close to 10 bar as possible
- minimise the use of the holder
- make sure that end of day stock was the same as start of day stock

Although the gas is supplied at a constate rate, the gas consumers on the do not take gas out the network at a constant rate. As demand can change at anytime, and the participant will only become aware of the change after it has happened, they need to be able to respond quickly. If demand is greater than supply then additional gas can be taken from line pack (i.e.high pressure pipes), the holder (i.e. a gas storage facility), and by increasing supply through the regulator. If demand is lower than supply then surplus gas has to be stored as line pack or in the holder, or supply has to be decreased through the regulator.

When it comes to making the changes, each participant has a choice of either acting alone or acting in co-ordination with the other team members. Optimal solutions to the problems they were set come from a co-ordinated effort because adjustments to the overall flow-rate of gas supplying the four areas had heavy financial penalties. Only by co-ordinating flow-rate changes with other areas could participants minimise or prevent overall flow-rate changes.

Procedure

The experimental procedure was as follows:

1. Participants were recruited in teams of four.

2. They were introduced to each other and given an initial introduction and briefing about the task.
3. Ethical matters were explained and the consent form was signed.
4. Biographical data were collected and each member was told which condition they were being tested in (i.e. abstract/virtual, proximal/distal) and given an identification name (e.g. North South, East or West).
5. They were then given their instructions and given a hands-on demonstration of how to control the gas network.
6. Participants undertook a one-hour training session before performing the task. All participants were given one-to-one assistance throughout this training
7. The team was asked to carry out the task with no assistance from the researchers. All participants were asked to work together as a team. The experimental phase lasted approximately one hour.
8. They were then paid £10, asked to sign a receipt, and thanked for their time and participation.

Coding and Analysis

The video data were coded by one of the researchers, on a minute-by-minute basis into one of four categories: strategic, tactical, opportunistic, and scrambled. This was done purely from the video and audio tapes together. To check the reliability of the coding, three of the 24 tapes were chosen at random and analysed by another researcher who was also trained in the coding system. The analysis of the two independent categorisations showed a high degree of correlation (Spearman's rho = 0.793, $p<0.001$). This means that a high degree of confidence may be placed in the categorisation system.

The COCOM data were then analysed using the Mann Whitney U test to see if there were any statistically significant differences between the experimental group. These data are reported in the results section. As the data were non-parametric, it was not possible to compute a 2-way ANOVA.

RESULTS

The COCOM data was complied into this single table to test the hypothesis that people move between control modes in a linear manner. As the data in table 1 illustrate, our findings support Hollnagel's (1993) hypothesis. In fact, only five transitions (2 transitions from Strategic to Opportunistic and 3 transitions from Tactical to Scrambled) are contrary to the COCOM model.

FROM/TO	Strategic	Tactical	Opportunistic	Scrambled
Strategic		17	2	0
Tactical	5		87	3
Opportunistic	0	77		44
Scrambled	0	0	45	

Table 1. Transitions between COCOM modes

It is interesting to note that we did not find any transitions between the 'strategic' and 'scrambled' control modes. This might be due to the participants not experiencing any situations where the environment changed so rapidly that they did not pass through the intervening 'tactical' and 'opportunistic' modes, or the vagaries of the categorisation scheme.

From reviewing the returns up through the control modes (i.e. scrambled to opportunistic, opportunistic to tactical) one can see that there is a freedom of movement over the course of the experimental trial. It is certainly not the case that there is a gradual deterioration throughout the course of the experiment.

The contextual control model (COCOM) was tested in terms of the four levels of control modes (i.e. strategic, tactical, opportunistic and scrambled) in the experimental tasks. The results show that teams spend more time in tactical control in the proximal condition (both abstract and virtual groups) and more time in scrambled control in the virtual-distal group. From this analysis, close proximity of team members looks preferable, as shown in figure 4.

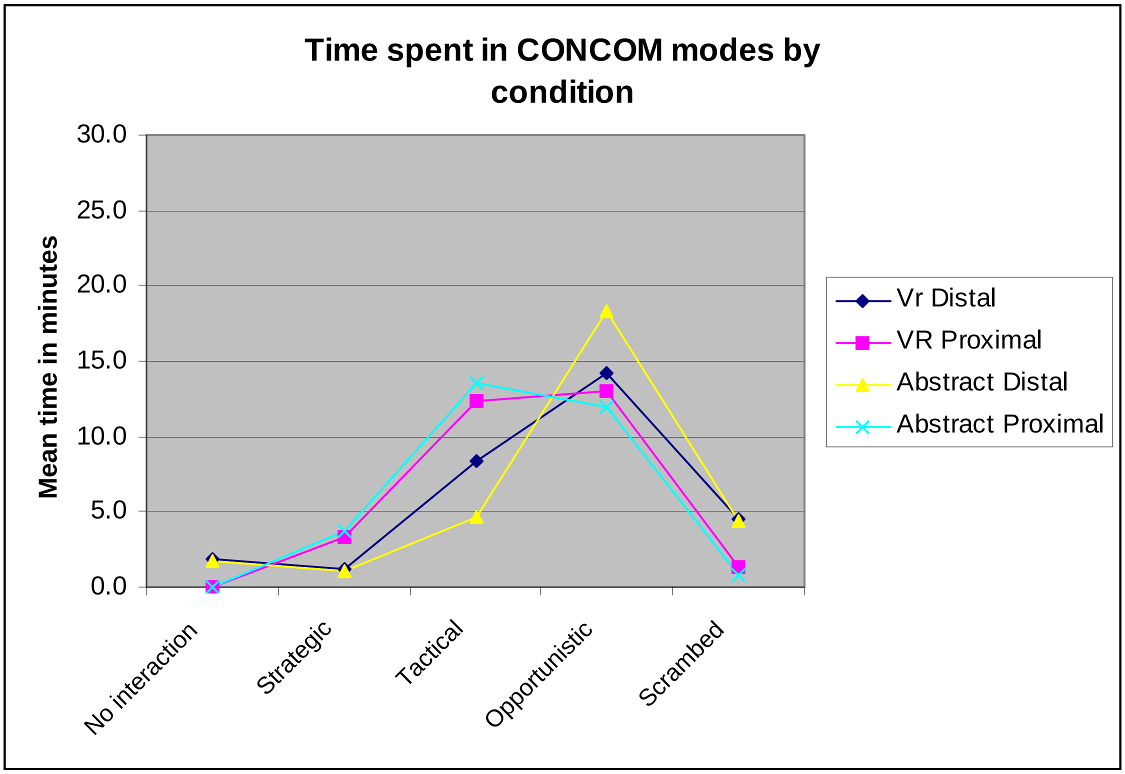

Figure 4. Mean COCOM time data for the experimental groups

Analysis of the time spent was conducted for each of the control modes in each of the experimental conditions. The Bonferroni correction was applied to take account of multiple comparisons. The results are summarised in table 2.

		DISTAL		PROXIMAL	
		ABSTRACT	**VIRTUAL**	**ABSTRACT**	**VIRTUAL**
DISTAL	**ABSTRACT**		Opportunistic DA>DV	Tactical PA>DA	Tactical PV>DA
	VIRTUAL			Scrambled DV>PA	Scrambled DV>PV
PROXIMAL	**ABSTRACT**				N/A
	VIRTUAL				

Table 2. Summary of significant differences for time in CONCOM (where DA = Distal Abstract, DV = Distal Virtial, PA = Proximal Abstract, PV = Proximal Virtual)

As table 2 shows, the abstract-distal groups spent significantly more time in opportunistic control than the virtual-distal group ($U=2.5$, $p<0.01$). Close proximity seems to favour tactical control, as the abstract-proximal group spent more time in tactical control than the abstract-distal group ($U=2.5$, $p<0.01$) and the virtual-proximal group also spent more time in tactical control than the abstract-distal group ($U=0.5$, $p<0.005$). Similarly, close proximity seems to work in favour of reducing scrambled control, as the abstract-proximal group spent less time in scrambled control than the virtual-distal group ($U=1.0$, $p<0.005$) and the virtual-proximal group also spent less time in scrambled control than the virtual-distal group ($U=2.5$, $p<0.01$).

DISCUSSION

This analysis shows that the manipulation of the experimental conditions lead to different types of team behaviour. Assuming that tactical behaviour is more desirable than scrambled, the results lead us to propose that the proximal condition was superior to the distal condition. The study does seem to suggest that there is merit associated with the higher-level analysis of team behaviour inherent in the COCOM approach, and this is wholly concordant with more recent research approaches to the study and analysis of team working (Annett & Stanton, 2000). The analysis of team behaviour in context and the move away from atomistic descriptions seems to provide more manageable data as well as more insightful analysis. In viewing the video data it became clear that context was an extremely important influence on team behaviour, as Hollnagel wrote, *"actions are determined by context rather than by an inherent relation between them"* (p.152, 1993). He argues for a situated action view of planned behaviour, similar to the proposal by Suchman (1987). From the presented model, people are less bound by the immediate system context at the strategic end of the spectrum**.** Our view is that the organisational context determines proactive behaviour whereas process-demand context determines reactive behaviour (Stanton & Ashleigh, 2000). This seems to fit with Hollnagel's views regarding main parameters governing control modes.

This notion was also endorsed by observing the video data, as differences in verbal and non-verbal behaviours, were obvious across the conditions. When physically remote, team members were obviously less interactive; in fact at the beginning of some trials there were several minutes when no-one spoke to each other. This may have accounted for the fact that regardless of interface type, these teams spent less time on strategic and tactical control. It also meant that they were more likely to become insular and make individual decisions and control actions, rather than working collaboratively as part of a team. This was particularly obvious in the abstract-distal condition where at times team members tending to be reactive rather than proactive. More planning was required in this condition because this interface only gave end-of-day predictions. In comparison with the virtual display, there was less information to observe on screen and less need to physically search for in terms of details relevant to the task. This should have freed up more planning time, but there was little evidence of this. Rather than helping people in their task, this tended hinder team members when they were remote from each other. Instead of using this 'spare' capacity in discussing long term strategies and talk about what they *could* do, they tended to work independently. If, after the first couple of simulation steps, participants found they had radically emergent shapes from the polygon parameters set, they were then driven into action. This is a typical example of opportunistic control. Within a control room situation therefore when isolating operators, consideration should be given for bespoke training in such team skills as planning strategies, evaluating action, feedback, and joint decision making. If the only communication between operators is a video screen and/or telecommunication, group dynamics can *feel* drastically different.

In contrast, when teams worked together in the same location, the interface type appeared to have had less of an effect on their control actions. Generally, there was a lot more evidence of social interaction, something that was noted to be lacking in the distal conditions. People physically remote tended to focus more exclusively on the task. As the results show, the participants in the proximal condition spent more time on planning activities, (e.g. tactical control). Participants using the polygon displays in the proximal condition appeared less system driven than the other groups as evidenced by the reduction in scrambled control. The highest performing team overall was in the abstract-proximal condition, their success was due to their constant planning, evaluating and feeding back to each other. There was also some evidence of different team roles (Belbin, 1993) from the videotape. Co-ordinators tended to evolve usually initiating plans and distributing tasks to others. Planners worked out the mathematics and come up with a team solution. People working in the same space, tended to be quicker at grasping the objective of the task and may share the same mental model. There was greater co-operation shown between members in the proximal groups. If someone was having trouble or misunderstood something, his/her team-mate would quickly offer guidance and support.

Using a different system of categorisation, Stanton & Ashleigh (2000) found some differences in the ratio of proactive to reactive team behaviour in real control rooms. Their scheme identified five behavioural categories. These were: planning (activities that require strategic planning and driving the system), awareness (activities that maintain an awareness of system state), sharing (activities that share own and others knowledge of the system), driven (activities that are driven by the system in real-time) and other (any other activity not classified). Stanton & Ashleigh (2000) identify three main independent variables in their naturalistic study, the time-of-year the studies were undertaken (i.e. winter or summer), the stage of team development (i.e. under 2 months or over 10 months) and the structure of the team configuration (i.e. hierarchy or heterarchy). The time-of-year differences are perhaps the least interesting but do highlight differences in activities associated with continuous processes. They observed that the teams studied in winter were engaged in more 'planning' and 'awareness' activities (i.e. information gathering behaviours) than those observed in the summer months. Rather more interesting is the finding that newer teams engage in more 'information 'sharing' activities than their more mature counterparts. This may reflect their stage of development, and as time progresses less of these activities might be observed as the individuals get to know and trust each other. Finally, the structural differences between the teams also appear to have had some effect on the activities of the teams. The hierarchical teams spent a greater amount of time in system 'driven' activities than the heterarchical teams. Given that Hollnagel (1993) argues that strategic control (e.g. 'planning' and 'awareness' activities) is superior to reactive control (e.g. system 'driven' activities) we may conclude that there may be some performance gains associated with heterarchical teams.

Returning to the findings from the current study, the use of the COCOM approach has led us to suspect that we should design working environments that encourage the more strategic and tactical activities and support the opportunistic activities when they are unavoidable. Design should attempt avoid forcing teams into scrambled activity wherever possible. Our data suggest that team proximity plays a large part in encouraging a more planned approach. We are optimistic that this study will encourage more researchers to explore the COCOM framework and further extend the theoretical development of the contextual research into human supervisory control.

CONCLUSIONS

In conclusion, the results support Hollnagel’s contextual control model (COCOM). Not only was it possible to classify team behaviour into the four categories reliably (i.e.

strategic, tactical, opportunistic and scrambled), but also the movement between the control modes (i.e. from strategic to tactical to opportunistic to scrambled and vice versa) was as Hollnagel's hypothesis predicted. We consider this to be the first independent test of the model. The use of the model also revealed differences between the behaviour of the teams. The results show that teams spend more time in tactical control in the proximal condition (both abstract and analogue groups) and more time in scrambled control in the analogue-distal group. Future research should examine the COCOM in more established teams.

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