The role of error processing in the contextual interference effect during the training of perceptual-cognitive skills

David P. Broadbent[1, 2], Joe Causer[1], A. Mark Williams[3] & Paul R. Ford[4]

[1] Research Institute of Sport and Exercise Sciences, Liverpool John Moores University
[2] Division of Sport, Health and Exercise, Department of Life Sciences, Brunel University London
[3] Department of Health, Kinesiology, and Recreation, University of Utah
[4] Centre for Sport and Exercise Science and Medicine, University of Brighton

Abstract

The contextual interference (CI) effect refers to the learning benefits that occur from a random compared to blocked practice order. In this paper, the cognitive effort explanation for the CI effect was examined by investigating the role of error processing. In two experiments, a perceptual-cognitive task was used in which participants anticipated three different tennis skills across a pre-test, three practice sessions, and retention test. During practice, the skills were presented in either a random or blocked practice order. In Experiment 1, cognitive effort was examined using a probe reaction time task. In Experiment 2, cognitive effort was manipulated for two groups by inserting a cognitively demanding secondary task into the inter-trial interval. The CI effect was found in both experiments as the random groups displayed superior learning in the retention test compared to the blocked groups. Cognitive effort during practice was greater in random compared to blocked practice groups in Experiment 1. In Experiment 2, greater decrements in secondary task performance following an error were reported for the random group when compared to the blocked group. The suggestion is that not only the frequent switching of tasks in randomized orders causes increased cognitive effort and the CI effect, but it is also error processing in combination with task switching. Findings extend the cognitive effort explanation for the CI effect and propose an alternative hypothesis highlighting the role of error processing.

Keywords: Cognitive effort; anticipatory judgement; practice structure; perceptual learning; secondary task

General Introduction

The manner in which practice is structured affects skill acquisition. The contextual interference (CI) effect refers to the differential impact on skill acquisition of a random versus blocked practice schedule. A random schedule, or high CI, involves switching between a number of tasks or actions during practice (e.g., CBA ACB BAC). In contrast, a blocked schedule of practice, or low CI, involves a number of tasks or actions being executed separately from one another in a repetitive manner (e.g., AAA BBB CCC). A random schedule of practice results in less improvement during practice, but promotes greater retention and transfer of skill, when compared to a blocked schedule of practice (Shea & Morgan, 1979).

While the CI effect is a robust finding, debate still remains around the underlying mechanisms of this phenomenon (Magill & Hall, 1990). In the current paper, the cognitive effort from task switching hypotheses for the CI effect is tested and an alternative hypothesis involving the processing of errors is examined. To our knowledge, the role of error processing and its effect on cognitive effort (Lam, Masters, & Maxwell, 2010) has not previously been investigated in conjunction with the CI effect and could provide a novel explanation for the mechanisms underpinning this phenomenon. Moreover, little attention has been given to the effects of different practice schedules on the learning of anticipatory judgements (for an exception, see Broadbent, Causer, Ford, & Williams, 2015a). Much of the research surrounding the CI effect appears to predict that the planning, selection, and execution of *motor skill* is essential for the interference caused between tasks (Magill & Hall, 1990). We examined the CI effect using a perceptual-cognitive task rather than the typical perceptual-motor task in order to provide a unique insight into the mechanisms underpinning this phenomenon (Memmert et al., 2009).

The CI effect is a robust finding for motor skill acquisition (for reviews, see Brady, 1998; 2008; Lee, 2012; Magill & Hall, 1990; Merbah & Meulemans, 2011; Wright, Verwey, Buchanan, Chen, Rhee, & Immink, 2015). In the seminal paper by Shea and Morgan (1979), participants performed three versions of a simple barrier knockdown motor task practiced in either a random or blocked order. During practice, the blocked order group demonstrated faster total movement times compared to the random order group. However, on the retention and transfer test, the random practice group had a faster total movement time compared to the blocked group, indicating superior learning. The CI effect has been shown in the acquisition of a wide variety of laboratory-based (Pauwels, Swinnen, & Beets, 2014; Wright, Magnuson, & Black, 2005; Lee, Wulf, & Schmidt, 1992; Magnuson & Wright, 2004), and applied motor tasks (Goode & Magill, 1986; Ollis, Button, & Fairweather, 2005; Smith & Davies, 1995; Hall, Domingues, & Cavazos, 1994).

Two theories have been proposed to explain the underlying mechanisms of the CI effect, namely the *elaborative processing hypothesis* and the *action plan reconstruction hypothesis*. Both theories detail how greater cognitive effort occurs during random compared to blocked ordered practice due to task switching (Lee, 2012). Cognitive effort is the mental work involved in selecting and executing decisions and actions (Lee, Swinnen, & Serrien, 1994). According to the elaborative processing hypothesis, a random practice order leads to greater cognitive effort through intra- and inter-task comparisons because the skills differ from trial to trial (Shea & Titzer, 1993; Wright, 1991; Wright, Li, & Whitacre, 1992). In comparison, during blocked practice the opportunity for contrasting the different actions is minimized to only intra-task comparisons due to the repetitive nature of the practice order (Shea & Zimny, 1983; 1988). Lin and colleagues (Lin, Fisher, Winstein, Wu, & Gordon, 2008; Lin, Fisher, Wu, Ko, Lee, & Winstein, 2009; Lin, Winstein, Fisher, & Wu, 2010) investigated the CI effect using transcranial magnetic stimulation (TMS). In one study, novice participants practiced three different arm movement tasks in either a blocked or random practice structure. Single TMS pulses were synchronized to each inter-trial interval to reduce information processing during the two practice conditions. The typical CI effect was found for groups without TMS. However, the random practice advantage was eliminated when TMS was applied between random practice trials, as it was suggested to prevent them from conducting elaborative processing (Lin et al., 2008).

According to the *action plan reconstruction hypothesis*, random practice requires more effortful processing because the action plan for the next trial has been forgotten and must be recalled. It is forgotten due to the interference of executing a different preceding action and must be retrieved from working memory for the next action. In comparison, blocked practice involves using the same action plan on each trial so no forgetting or retrieval/reconstruction processes occur (Lee & Magill, 1983, 1985; Lee, Magill, & Weeks, 1985). One method to examine this hypothesis has been to prevent the forgetting that is predicted to occur between trials in a random practice condition. For example, during the inter-trial period participants observe a computer-generated demonstration of the movement pattern to be performed (Lee, Wishart, Cunningham, & Carnahan, 1997). Observing a congruent demonstration in the inter-trial period leads to similar performance from the random practice groups compared to blocked practice groups in both practice and retention tests, because it reduces forgetting and reconstructive processes. Cross, Schmidt, and Grafton (2007) used a key-press task to examine the neural substrates of the CI effect with functional magnetic resonance imaging. Consistent with the reconstruction hypothesis, the random group showed greater activity in the planning regions of the brain, when compared to the blocked practice group.

Both the elaboration and action plan reconstruction hypotheses have led to the highly cited explanation that *task switching* causes the increased cognitive effort found during random practice (Li & Wright, 2000). However, alternative explanations could provide a greater insight into the mechanisms involved. Researchers from the motor learning domain suggest that *error processing* increases cognitive effort through the demands associated with success or failure on a task (Holroyd, Yeung, Coles, & Cohen, 2005; Koehn, Dickinson, & Goodman, 2008). When errors occur, performers identify discrepancies between the actual outcome and the desired goal (Rabbitt, 1966, 1967). In addition, they generate rules, hypotheses and knowledge about future task requirements so as to improve subsequent performance (Maxwell, Masters, Kerr, & Weedon, 2001). Therefore, an error trial leads to greater cognitive effort due to the additional processing that takes place when compared to an errorless trial (Lam et al., 2010). In the current paper, we examine the proposal that it is not simply the switching of tasks that increases cognitive effort through elaborative and/or reconstructive processes, but that error processing also has an important role in this phenomenon by increasing the load in working memory during random practice when errors occur. This finding may link to findings that random practice causes an implicit mode of learning due an increased load in working memory (Rendell, Masters, Farrow, & Morris, 2011).

The CI effect has recently been extended to perceptual-cognitive skills training, offering a new domain through to which investigate the underlying mechanisms of this phenomenon (Broadbent et al., 2015a; Helsdingen, van Gog, & van Merriënboer, 2011a; 2011b). The CI effect originated from a non-motor task domain, the verbal learning literature, where Battig (1972; 1979) referred to it first as ‘inter-task interference’. The elaborative processing hypothesis is directly linked to this and other work on motor learning and, thus, support for this hypothesis would be expected in the perceptual-cognitive skills domain (Broadbent et al., 2015a; Memmert et al., 2009). In contrast, the definition for the action plan reconstruction hypothesis states that for an upcoming task in random practice ‘a person must retrieve the appropriate *motor program* representing that action and then add the parameters specific to the constraints and goal of the task to be performed' (Magill & Hall, 1990, pp. 271). Finding the CI effect in verbal or perceptual-cognitive tasks contradicts this definition of the action plan reconstruction hypothesis due to the absence of a physical action and an associated motor program. However, there is strong evidence to suggest that observing a movement can activate the brain via the mirror neuron system and excite the motor system through resonant mechanisms (e.g., Denis, Rowe, Williams & Milne, 2016; Kilner, Vargas, Duval, Blakemore & Sirigu, 2004). In previous research on the CI effect using a perceptual task with skilled participants (Broadbent et al., 2015a), the perceived action might have resonated within the individuals own motor system activating an action plan for completing the skill and enabling the individual to anticipate, rather than react to, the actions of others (Aglioti, Cesari, Romani & Urgesi, 2008). Alternatively, other researchers using non-motor tasks (Carlson, Sullivan & Schneider, 1989; Carlson & Yaure, 1988; Helsdingen et al., 2011a; 2011b) support the action plan reconstruction hypothesis explaining that random practice forces learners to discard the task 'strategy' (Helsdingen et al., 2011a; 2011b) or 'processing plan' (Carlson & Yaure, 1988) between tasks and either retrieve or reconstruct a new strategy/plan for successive tasks. This notion indicates that the term *action plan* is not directly linked to a *motor* action plan, but rather suggests that for any task to be complete, be it motor or perceptual, a plan must be placed into working memory for the task to be carried out (Ericsson & Kintsch, 1995). The disparity around the definition of the action plan reconstruction hypothesis is still yet to be fully acknowledged in the literature. The training of perceptual-cognitive skill offers a novel domain to directly examine whether elaborative and/or reconstructive processes take place during the CI effect and could allow for the proposal of new terminology and definitions to encompass both motor and perceptual tasks.

In this paper, we provide insight into the well-established explanations for the CI effect, namely the elaborative processing hypothesis and the action plan reconstruction hypothesis, by investigating them in the novel domain of perceptual-cognitive skills training. Furthermore, an alternative hypothesis is examined to address whether the increased cognitive effort found for random practice is as a consequence of task switching in conjunction with error processing. Cognitive effort will be investigated across two experiments in which novice tennis players anticipate three different skills shown on life-sized video in either a random or blocked practice order. Anticipation performance will be recorded during a pre-test, across three practice sessions, and on a retention test. It is expected that the CI effect will occur in both experiments with the blocked group outperforming the random group during practice, but in the retention test the random group will show superior learning compared to the blocked group. Furthermore, it is predicted that the random group will exhibit greater amounts of cognitive effort across practice compared to the blocked group, either supporting one or both of the action plan reconstruction hypothesis and the elaborative processing hypothesis from the CI literature. Moreover, cognitive effort is predicted to be greater during random practice on error trials, compared to blocked practice and errorless trials, as the combination between task switching and error processing increases the load in working memory.

Experiment 1

Cognitive effort is a flexible capacity that can be subdivided among tasks so long as the demands do not exceed the available capacity of attention (Kahneman, 1973). When a task demands a high level of cognitive effort, there is a smaller capacity left available to perform other tasks. Attentional capacity is often examined in both the CI and error literature using the dual- or secondary-task paradigm, which involves performance of two tasks simultaneously (Abernethy, Maxwell, Masters, van der Kamp, & Jackson, 2007). Discrete secondary-tasks are often used, such as the probe reaction time (PRT), in which participants respond to an auditory tone while performing the primary task (Abernethy et al., 2007). The greater the cognitive demands of the primary task at any given moment, the slower the reaction time on the secondary task (Goh, Gordon, Sullivan, & Winstein, 2014). PRT tasks have been used to examine the underlying mechanisms of the CI effect in motor skill tasks (Li & Wright, 2000; Rendell et al., 2011), providing support for both the reconstructive and elaborative hypothesis. However, researchers are yet to examine these hypotheses for the acquisition of perceptual-cognitive skills. PRT tasks have also been used to examine the effect of errors on cognitive effort (Lam et al., 2010), showing that cognitive effort is greater on trials involving an error when compared to errorless trials. No researchers to our knowledge have examined the effects of errors on cognitive effort as a function of the CI effect.

We examine the acquisition of anticipatory judgements under random or blocked practice conditions and the role of cognitive effort from task switching and error processing in the CI effect. Novice tennis players' anticipated three different tennis skills shown as life-sized videos in either random or blocked schedules across a pre-test, three practice sessions, and a retention test. In accordance with the CI effect, it is expected that the blocked group will demonstrate superior response accuracy (RA) across practice compared to the random group, but in the retention test the random group will demonstrate superior RA compared to the blocked group (Shea & Morgan, 1979). During practice, cognitive effort will be examined by inserting a PRT into two phases of a trial in accordance with the two hypotheses from the CI literature. First, the action plan reconstruction hypothesis predicts greater cognitive effort for the random group in the *observation phase* of a trial, when compared to the blocked group. This phase is when participants are told the requirements of the upcoming task and must retrieve and reconstruct an appropriate action plan (Li & Wright 2000). Second, the elaborative processing hypothesis predicts greater cognitive effort for the random group during the *feedback phase* of a trial. Feedback is gained on performance in this phase that is compared, through intra- and inter-task comparisons, to previous successful and unsuccessful trials (Li & Wright 2000). During practice, cognitive effort and error processing will be analyzed using decision time (DT) from the secondary task in the observation and feedback phase, and from the primary task in the response phase (Lam et al., 2010). DT will be compared for a blocked and random schedule of practice following an error and an errorless trial. It is expected that following an error the random practice group will exhibit significantly greater cognitive effort in the observation, response, and feedback phase of a trial compared to the blocked group and errorless trials.

Method

Participants

Participants were 24 undergraduate students who were novice tennis players with no competition experience in the sport. They were randomly divided into either a blocked practice group (*n* = 12; 4 females and 8 males; *M* age = 23.3 years, *SD* = 4.5) or a random practice group (*n* = 12; 4 females and 8 males; *M* age = 23.5 years, *SD* = 3.2). No group differences were found for the primary anticipation task at pre-test between the blocked (*M* = 52%, *SD* = 4) and random groups (*M* = 48%, *SD* = 9), *p* =.17, *d* = .60. Informed consent was obtained from the participants prior to participation. The research was conducted in accordance with the ethical guidelines of the lead institution.

Task and apparatus

The task required participants to anticipate the landing location of tennis shots executed by a player on-screen. To create the video footage, three different intermediate level tennis players were filmed on a standard tennis court executing three shots: forehand groundstroke; forehand smash; and forehand volley (Broadbent et al., 2015a). The video was filmed from a camera placed on the center of the baseline of the tennis court at a height of 1.5 m to provide a representative view of the court from the participants’ perspective. The footage was made into clips using video editing software (Adobe Premier CS5, San Jose, USA). Each video clip began with a black screen and the trial number, which appeared for 3 seconds. Subsequently, the tennis film began, which consisted of the onscreen player standing at one of three central locations on the other side of the net, the ball arriving to the player, the player moving to the ball, and swinging the racket. Clips were occluded at ball-racket contact when the screen went black for 3 seconds, before the next trial began. Shots landed in four locations on the participant’s side of the court, which were occluded on the video: left short; right short; left deep; and right deep.

The experimental apparatus and setup is shown in Figure 1. Participants stood 4 m from the center of a 2.74 x 3.66 m projection screen (Cinefold Projection Sheet, Draper Inc., Spiceland, IN, USA) on which the test films were projected (Hitachi CP-X345, Yokohama, Japan). The size of the image approximated the life-size proportions normally experienced in game situations when players are positioned on the baseline of the court. Participants wore a lapel microphone (Seinheisser EW 100 ENG G2 RF, Germany). They were required to respond quickly and accurately to the onscreen shot by verbally stating a number between one and four that corresponded to the area of the court where the ball could bounce (1 = left short; 2 = right short; 3 = left deep; 4 = right deep). Participants did not perform a movement response as in previous research (Broadbent et al., 2015a), but stood still with a tennis racket in hand due to the movement restrictions caused by the secondary task. As stated previously, the action plan reconstruction hypothesis states that the motor program for an action must be retrieved and an action executed for interference to occur (e.g., Magill & Hall, 1990). However, there is evidence to suggest that observing an action activates the individual’s motor system enabling anticipatory behavior (e.g., Denis et al., 2016; Kilner et al., 2004).

Therefore, it was predicted that a perceptual response would not cause differences in action planning compared to previous research using motor responses, as similar processing will occur due to resonant mechanisms in the brain (e.g., Aglioti et al., 2008).

A PRT secondary task was added to the clips shown during the practice phase. High (2,500 Hz) and low frequency (300 Hz) tones that were 240 ms in duration were overlaid on the clips using video editing software (Adobe Premier CS5, San Jose, USA). Probes were presented in a way that their onset could not be predicted through randomizing inter-stimulus intervals (Wulf, McNevin, & Shea, 2001) and inserting catch trials in which a probe did not occur (Salmoni, Sullivan, & Starkes, 1976). Participants were required to react to the PRT task on high, but not low, tones by pressing a button that was ergonomically attached to the tennis racket. The microphone and the button press were synchronized and analyzed with a developed algorithm through the computing environment MATLAB (Mathworks R2007, UK). This latter procedure allowed the verbal anticipation response by the participant, the onset of the high tones, and the moment the participant pressed the button on the racket to be recorded, providing DT data on each button press to a high tone. There were 54 high tones, 54 low tones and 36 catch trials with two of these in each phase of each trial. The high tones were present on approximately 40% of trials. Additionally, a different tone was added at the beginning of each practice video, two seconds before the first trial began, which was used as a reference point for analyzing DT in the verbal responses.

Procedure

Participants took part in a pre-test, three practice sessions, and a 10 minute retention test. The pre-test and practice blocks contained 36 trials each and the retention test consisted of 36 trials in a blocked order and 36 trials in random order counterbalanced across participants to ensure there was no bias towards either group (Broadbent et al., 2015a; Lin et al., 2008; 2009; 2010). Participants were informed of the response requirements for the films prior to testing. Pilot work ensured the clips were of similar difficulty and no clips were repeated across the different phases. The 36 trials in each phase comprised of 12 forehand groundstrokes, 12 forehand smashes, and 12 forehand volleys. Each set of 12 shot trials comprised of three trials to each of four locations on the court, which were occluded on the video: left short; right short; left deep; and right deep. The pre-test trials were structured in a blocked order so that the three shots were in three separate sets each containing either forehand groundstrokes, smashes, or volleys together.

For the practice phase, three different films were constructed corresponding to each of the three practice sessions. For the blocked group, the clips were arranged in each session so that all groundstrokes were together, all smashes were together, and all volleys were together. For the random group, the clips were placed in a quasi-random order where none of the three shot-types was repeated more than twice in a row. Participants received two presentations of the same clip during each trial in the practice phase. The first video, termed the observation phase, contained clips that were temporally occluded at ball-racket contact and that occurred before the participant response. The second video, termed the feedback phase, occurred after their response and was not occluded, so that participants viewed the full clip and received feedback as to where the ball actually landed.

Participants were informed of the response requirements for the PRT task prior to practice. For each participant, the three practice sessions were split into one practice block with no tones, one block with tones across the first video (observation phase), and one block with tones across the second video (feedback phase). These practice blocks were counterbalanced across participants (see Figure 2a). Participants also completed a PRT task alone prior to the experiment with no primary task so as to measure their base reaction time. Base level RT did not differ between the blocked group (*M* = 257 ms, *SD* = 61) and random group (*M* = 272 ms, *SD* = 57), *p* = .54, *d* = .27.

Data analysis

The dependent variables for the primary anticipation task were RA and DT. RA was expressed as the percentage of successful trials in which the response was the same as the location of the ball's landing on the court. DT (ms) was calculated as the difference between the time of the verbal response on each trial and the time of ball-racket contact or temporal occlusion. Responses initiated prior to ball-racket contact or occlusion received a negative value. RA and DT in the primary task were analyzed using a 2 Group (blocked, random) x 3 Session (pre-test, practice, retention) mixed-design ANOVA, with repeated measures on the last factor. For all ANOVAs partial-eta squared was calculated for effect size. Pairwise comparisons were used to follow up any significant main effects. For significant interactions a planned comparison was used to address the specific a priori hypotheses on the retention test. For the planned comparison, Cohens d was calculated for effect size.

The role of errors on cognitive effort as a function of blocked and random schedules of practice was examined using mean DT collapsed across all practice phases for the primary task. Analysis was conducted on the trial *following* an error as error processing occurs following feedback once the subject is aware of the error they have made and the nature of the error (Lam et al., 2010). The blocked group had approximately 58% errorless trials and 42% errorful trials. The random group had approximately 50% errorless and errorful trials. A 2 Group x 2 Error (errorless, error) mixed design ANOVA with repeated measure on the last factor was used to analyze DT in the primary anticipation task. Pairwise comparisons were used for any significant main effects. For any interactions, planned comparisons were used to address the specific a priori hypotheses. Updated alpha values are reported throughout.

The dependent variable for the secondary task was DT, which was calculated as the difference between the onset of the high tone on each trial and the button press by the participant. The role of errors was also analyzed for the secondary task in the observation and feedback phase separately. Secondary task DT was analyzed using a 2 Group x 2 Phase (observation phase, feedback phase) x 2 Error (errorless, error) ANOVA, with repeated measures on the last factor. Pairwise comparisons were used for any significant main effects. For any interactions, planned comparisons were used to address the specific a priori hypotheses. In order to limit the potential inflation of Type-1 errors through multiple comparisons, each alpha level was adjusted using the Bonferroni correction method. Updated alpha values are reported throughout.

Results

Primary anticipation task

Response accuracy. Figure 3 shows mean RA for the two groups in the pre-test, during practice, and in the retention test. A 2 Group x 3 Session ANOVA on RA revealed no group main effect, *F* (1, 22) = 1.23, p =.28, $\eta_p^2 = .05$. There was a significant main effect for session, *F* (2, 44) = 12.16, $p < .01$, $\eta_p^2 = .36$. RA in the pre-test (*M* = 50%, *SD* = 7) and practice (*M* = 54%, *SD* = 7) were significantly lower than in the retention tests (*M* = 58%, *SD* = 7), $p < .01$ and $p = .01$ respectively. There was a Group x Session interaction, *F* (2, 44) = 9.94, $p < .01$, $\eta_p^2 = .31$. No differences were found for RA between the groups in the pre-test as reported in the method section. Across practice the blocked group (*M* = 58%, *SD* = 6) had significantly greater accuracy compared to the random group (*M* = 50%, *SD* = 6), $p < .01$, d = 1.33. In the retention test, a planned comparison revealed that the random group (*M* = 61%, *SD* = 6) demonstrated significantly greater accuracy compared to the blocked group (*M* = 55%, *SD* = 6), $p = .03$, $d = .92$.

Decision time. Table 1 shows mean DT in the primary task for the two groups across the pre-test, practice, and retention test. A 2 Group x 3 Session ANOVA on DT revealed no Group main effect, *F* (1, 22) = .04, $p = .85$, $\eta_p^2 < .01$, Session main effect, *F* (2, 44) = .53, $p = .59$, $\eta_p^2 = .02$, or interaction, *F* (2, 44) = 1.00, $p = .36$, $\eta_p^2 = .04$.

Error analysis. Table 2 shows the mean DT of the two groups on trials following error and errorless trials in the practice phase. A 2 Group x 2 Error ANOVA on DT revealed no group main effect, F (1, 22) = .14, p = .71, η_p^2 = .01, error main effect, F (1, 22) = .58, p = .46, η_p^2 = .03, or interaction, F (1, 22) = 3.10, p = .09, η_p^2 = .12.

Secondary task

Decision time. Figure 4 shows mean DT for the two groups on the PRT task across the observation and feedback phases during practice. In order to assess whether the secondary task had affected RA in the primary task, a one-way ANOVA on RA in the primary task between tone conditions was used. RA was not different between the tone only condition (M = 54%, SD = 10), observation phase (M = 53%, SD = 9), and the feedback phase (M = 55%, SD = 6), F (2, 46) = .48, p = .62, η_p^2 = .02, suggesting that the secondary task had not affected RA in the primary task, supporting previous research (Goh et al., 2014).

A 2 Group x 2 Phase x 2 Error ANOVA revealed a significant group main effect for DT, F (1, 22) = 5.62, p = .03, η_p^2 = .21. The blocked group (M = 401 ms, SD = 94) had a significantly faster DT compared to the random group (M = 507 ms, SD = 136), p = .03. There was no main effect for phase, F (1, 22) = 1.33, p = .26, η_p^2 = .06, and no Group x Phase interaction, F (1, 22) = .01, p = .99, η_p^2 < .01, indicating that the random group had a significantly slower DT across the observation and feedback phases during practice when compared to the blocked group.

Error analysis. Table 2 shows mean DT for the secondary task of the blocked and random groups as a function of performance success (errorless, error) in the previous trial. The 2 Group x 2 Phase x 2 Error ANOVA on DT revealed a significant Phase x Error interaction, F (1, 22) = 5.28, p = .03, η_p^2 = .19. The planned comparison showed that differences in DT approached significance between an errorless trial in the feedback phase (M = 476 ms, SD = 154) and the observation phase (M = 425 ms, SD = 126), p = .07, d = .36, whereas there was no difference for error trials between the two phases (*p* >.05). A follow up using Tukey's Honest Significance Test demonstrated the Phase x Error interaction was explained by this difference between the feedback and observation phase following errorless trials (*p* = .04), as all other comparisons were not significantly different (*p* > .05). No other interactions were significant, all *p* > .05.

Discussion

As predicted, in the primary anticipation task the traditional CI effect was found with the random practice group displaying superior response accuracy in the retention test compared to the blocked practice group (cf. Shea & Morgan, 1979). Moreover, the random schedule of practice exhibited greater cognitive effort as shown by slower PRT compared to a blocked schedule of practice. Greater cognitive effort was found in both the observation and feedback phase of a trial for the random when compared to the blocked schedule of practice. Findings suggest that additional cognitive processes are used before, and after, an executed trial in a random compared to blocked schedule of practice, supporting the idea that both reconstructive and elaborative processes underpin the CI effect (Li & Wright, 2000). With regards to the role of error processing in the CI effect, the data provided no support for this alternative hypothesis in either the observation or feedback phase. Findings suggest further research is required to either support or dispute this alternative hypothesis, perhaps by examining a different time-period during the practice trial such as the inter-trial interval.

Experiment 2

Researchers investigating the underlying mechanisms of the CI effect have often referred to the *inter-trial interval* as a critical time period when cognitive effort occurs (Magill & Hall, 1990). The elaboration hypothesis predicts that inserting a cognitively demanding task during the inter-trial interval will disrupt the elaborative processes taking place for a random schedule of practice and will diminish the superior learning of random practice (Lin et al., 2008; Lin et al., 2010). In contrast, the action plan reconstruction hypothesis predicts that a cognitively demanding task during the inter-trial interval will promote forgetting in a blocked schedule of practice and inadvertently increase the reconstructive processes, resulting in increased learning for blocked practice (Lee & Magill, 1983, 1985). In Experiment 1, evidence was not found for the hypothesis that error processing for a random schedule of practice may contribute to the greater cognitive effort compared to blocked schedule of practice. This hypothesis was investigated in the observation and feedback phase of a trial, but not in the inter-trial interval.

In Experiment 2, we manipulate cognitive effort in the inter-trial interval using a cognitively demanding task (Stroop test; Macleod, 1991). Including a secondary task allows for the cognitive demands of the primary task to be analyzed. If the primary task is cognitively demanding, the inclusion of a demanding secondary task will exceed the available capacity of working memory and cause decrements in secondary task performance. In comparison, if the primary task is less cognitively demanding, then both tasks can be performed efficiently (Abernethy et al., 2007). Novice participants were divided into blocked, random, blocked-Stroop (BStroop), and random-Stroop (RStroop) groups. It is expected that the CI effect will occur in the primary anticipation task for the two groups without the Stroop test. With regards to the two practice groups with the Stroop test inserted in the inter-trial interval, the elaborative processing hypothesis predicts that the RStroop group will have decrements in performance compared to the random group as the cognitively demanding task will interfere with the intra-task comparisons made during a random schedule of practice (Lin et al., 2008; Lin et al., 2010). Alternatively, the action plan reconstruction hypothesis predicts that the BStroop group will demonstrate superior learning compared to the blocked group because the secondary task in the interval will cause short-term forgetting, promoting reconstructive activity for the BStroop group (Lee & Magill, 1983, 1985; Simon & Bjork, 2002). Moreover, with regards to error processing, in the inter-trial interval the RStroop group are predicted to exhibit significantly greater cognitive effort following an error compared to an errorless trial. In contrast, the BStroop group is expected to show no differences in cognitive effort following an error and errorless trial due to the predicted lower amount of elaborative processing occurring in that practice structure.

Method

Participants

Participants were 56 undergraduate students who were novice tennis players with no competition experience in the sport. They were randomly divided into either a blocked group (*n* = 14; *M* age = 20.7 years, *SD* = 1.6), random group (*n* = 14; *M* age = 20.9 years, *SD* = 1.1), BStroop group (*n* = 14; *M* age = 20.9 years, *SD* = 1.4), or RStroop group (*n* = 14; *M* age = 21.1 years, *SD* = 1.1). Each group had 11 males and 3 females. No group differences for response accuracy were found at pre-test between the four groups, $p > .05$. Informed consent was obtained from the participants prior to participation. The research was conducted in accordance with the ethical guidelines of the lead institution.

Task and apparatus

The film clips and the protocol were the same as in Experiment 1 with a pre-practice-retention design. No PRT measure was used in this experiment. For the BStroop and RStroop groups (see Figure 2b), a Stroop test was inserted in the inter-trial interval of practice trials using video editing software (Adobe Premier CS5 software, San Jose, USA). The Stroop test was selected due to the high cognitive demands it places on working memory (Kane & Engle, 2003; Long & Prat, 2002). The Stroop test presents three color words, such as red, green, and blue, with a font color of text that is different to that of the word. On the video clips, a black screen appeared prior to the Stroop test on each trial that had either stated “color” or “word” in a large white font to inform participants of their response requirement. Participants were required to respond quickly and accurately by verbally stating either the word that was printed or the color that the word was printed in, as directed. Three words appeared consecutively following each trial of the primary task. Each word was presented on screen for 90 ms as pilot work demonstrated that this time allowed the task to be completed successfully, but was still challenging for the participants. The order of presentation was randomized so that participants were unaware of the response they had to provide prior to each of the 36 trials of the Stroop test. The randomized presentation requires a new action plan to be implemented into working memory on the subsequent trial, potentially causing more interference to the primary task (for a review of Stroop effect theory, see Macleod, 1991; 1992).

Procedure

The experimental apparatus, set up and procedure was the same as in Experiment 1(see Figure 2b), although there was no PRT task, and the pre-test contained a blocked (*n* = 18) and random (*n* =18) structure of practice so as not to favor either group. In addition, the Stroop test occurred after every trial in all three practice sessions for those two groups. The lapel microphone was synchronized and analyzed with a developed algorithm through the numerical computing environment MATLAB (Mathworks R2007, UK). It allowed the verbal response by the participant on both the primary anticipation task and the Stroop test to be recorded and later analyzed.

Data analysis

For the primary anticipation task, the dependent variables were the same as in Experiment 1 and were analyzed separately using three separate ANOVAs. To replicate the data analysis in Experiment 1, RA and DT in the primary task were analyzed using a 2 Group (blocked, random) x 3 Session (pre-test, practice, retention) mixed-design ANOVA, with repeated measures on the last factor. To analyze the additional groups, RA and DT in the primary task were analyzed using a 2 Group (blocked, BStroop) x 3 Session (pre-test, practice, retention) mixed-design ANOVA and a 2 Group (random, RStroop) x 3 Session (pre-test, practice, retention) mixed-design ANOVA. For all ANOVAs partial-eta squared was calculated for effect size. Pairwise comparisons were used to follow up any significant main effects. For significant interactions a planned comparison was used to address the specific a priori hypotheses on the retention test. For the planned comparison, Cohens d was calculated for effect size.

Analysis of DT as a measure of cognitive effort on trials *following* errors was conducted for the primary anticipation task. DT was analyzed following an errorless and error response in the previous trial for the blocked and random groups. The percentages for errorless and errorful trials for each group were: blocked group (58% errorless; 42% errorful trials), random group (50% errorless; 50% errorful trials), BStroop group (52% errorless; 48% errorful trials), RStroop group (52% errorless; 48% errorful trials). To replicate the analysis in Experiment 1, a 2 Group (blocked, random) x 2 Error mixed design ANOVA with repeated measure on the last factor was used to analyze DT in the primary anticipation task. To analyze the additional groups, DT was analyzed using a 2 Group (blocked, BStroop) x 2 Error mixed-design ANOVA and a 2 Group (random, RStroop) x 2 Error mixed-design ANOVA

For the Stroop test, the dependent variables were RA and DT. RA refers to the number of successful responses out of 108 trials and is defined as whether the color or word verbalized by the participant matched the trial requirements for the color or word displayed. DT (ms) was calculated as the difference between initiation of the verbal response on each Stroop trial and the moment the slide appeared on the screen. All responses were initiated after the slide appeared and received a positive value that was analyzed through MATLAB with the software extrapolating all the data points for the verbal responses. Separate 2 Group x 3 Practice mixed design ANOVAs with repeated measures on the last factor were used to analyze RA and DT on the Stroop test. The role of errors was also analyzed for DT on the Stroop test using a 2 Group x 2 Error mixed design ANOVA with repeated measure on the last factor. Pairwise comparisons were used to follow up any significant main effects. For significant interactions, planned comparisons were used to address any specific a priori hypotheses. Alpha level was adjusted using the Bonferroni correction method. Updated alpha values are reported throughout.

Results

Primary anticipation task

Response accuracy. Figure 5 shows mean RA for the four groups on the pre-test, three practice sessions, and the retention tests. A 2 Group (blocked, random) x 3 Session ANOVA revealed no group main effect, F (1, 26) = .30, p =.59, η_p^2 = .01. There was a significant main effect for session, F (2, 52) = 5.23, p = .01, η_p^2 = .17. RA in the retention test (M = 56%, SD = 6) was significantly greater compared to the pre-test (M = 51%, SD = 8), p = .02, whereas RA in practice (M = 54%, SD = 6) did not differ to the pre- and retention test. There was a significant Group x Session interaction, F (2, 52) = 8.47, p < .01, η_p^2 = .25. No between-group differences were found in the pre-test as shown in the methods section. Across practice the blocked group (M = 58%, SD = 5) were significantly more accurate than the random group (M = 50%, SD = 5), p < .01, d = 1.60. In the retention test, the random group (M = 58%, SD = 6) had significantly greater RA compared to the blocked group (M = 54%, SD = 5), p = .05, d = .77.

A 2 Group (blocked, BStroop) x 3 Session ANOVA revealed no group main effect, F (1, 26) = .43, p =.52, η_p^2 = .02. There was a significant main effect for session, F (2, 52) = 4.94, p = .01, η_p^2 = .16. RA in the retention test (M = 55%, SD = 5) was significantly greater compared to the pre-test (M = 51%, SD = 9), p = .05, whereas RA in practice (M = 54%, SD

= 7) did not differ to the pre- and retention test. There was a significant Group x Session interaction, *F* (2, 52) = 4.95, *p* = .01, η_p^2 = .16. No between-group differences were found in the pre-test as shown in the methods section. The blocked group (*M* = 58%, *SD* = 5) demonstrated superior RA across training compared to the BStroop group (*M* = 52%, *SD* = 7), *p* = .01, *d* = 1.07, but there were no between-group differences in RA in the retention test, *p* = .27, *d* = .44. The 2 Group (random, RStroop) x 3 Session ANOVA revealed no group main effect, *F* (1, 26) = .03, *p* =.86, η_p^2 < .01. There was a significant main effect for session, *F* (2, 52) = 8.25, *p* < .01, η_p^2 = .24. RA in the retention test (*M* = 57%, *SD* = 7) was significantly greater compared to the pre-test (*M* = 52%, *SD* = 7) and in practice (*M* = 51%, *SD* = 5), *p* = .01 and *p* < .01 respectively. There was no Group x Session interaction, *F* (2, 52) = 1.30, *p* = .28, η_p^2 = .05.

Decision time. A 2 Group (blocked, random) x 3 Session ANOVA revealed no group main effect, *F* (1, 26) = .69, *p* =.41, η_p^2 = .03. There was a significant main effect for session, *F* (2, 52) = 5.01, *p* = .01, η_p^2 = .16. DT in the retention test (*M* = 890 ms, *SD* = 227) and in practice (*M* = 895 ms, *SD* = 241) was significantly greater compared to the pre-test (*M* = 805 ms, *SD* = 185), *p* = .03 and *p* = .01 respectively. There was no Group x Session interaction, *F* (2, 52) = .56, *p* = .57, η_p^2 = .02.

A 2 Group (blocked, BStroop) x 3 Session ANOVA revealed no group main effect, *F* (1, 26) = .07, *p* =.79, η_p^2 < .01. There was a significant main effect for session, *F* (2, 52) = 6.96, *p* < .01, η_p^2 = .21. DT in practice (*M* = 870 ms, *SD* = 226) was significantly greater compared to the pre-test (*M* = 762 ms, *SD* = 224), *p* < .01, whereas DT in the retention test (*M* = 832 ms, *SD* = 237) did not differ to pre-test and practice. There was no Group x Session interaction, *F* (2, 52) = .60, *p* = .55, η_p^2 = .02. The 2 Group (random, RStroop) x 3 Session ANOVA revealed no group main effect, *F* (1, 26) = 1.51, *p* =.23, η_p^2 = .06. There was no main effect for session, *F* (2, 52) = 1.93, $p = .16$, $\eta_p^2 = .07$ and no Group x Session interaction, *F* (2, 52) = .12, $p = .89$, $\eta_p^2 = .01$.

Error analysis. Figure 6 shows mean DT in the primary task following an errorless or error response across the practice phase for the four groups. A 2 Group (blocked, random) x 2 Error mixed design ANOVA revealed no group main effect, *F* (1, 26) = .06, $p = .80$, $\eta_p^2 < .01$ and no Error main effect, *F* (1, 26) = 3.34, $p = .08$, $\eta_p^2 = .11$. However, there was a significant Group x Error interaction, *F* (1, 26) = 8.32, $p = .01$, $\eta_p^2 = .24$. The random practice group had significantly slower DT following an error (*M* = 930 ms, *SD* = 225) compared to following an errorless trial (*M* = 893 ms, *SD* = 217), *p* = .02, *d* = 0.81. In contrast, the blocked group showed no difference in DT following an error (*M* = 883 ms, *SD* = 269) compared to following an errorless trial (*M* = 892 ms, *SD* = 268), *p* = 1.00, *d* = 0.22.

A 2 Group (blocked, BStroop) x 2 Error mixed design ANOVA revealed no group main effect, *F* (1, 26) = .10, $p = .75$, $\eta_p^2 < .01$. There was a significant main effect of Error, *F* (1, 26) = 6.46, $p = .02$, $\eta_p^2 = .20$. DT was significantly slower following an errorless trial (*M* = 882 ms, *SD* = 225) compared to an error (*M* = 865 ms, *SD* = 229), *p* = .02. There was no Group x Error interaction, *F* (1, 26) = 1.66, $p = .21$, $\eta_p^2 = .06$. A 2 Group (random, RStroop) x 2 Error mixed design ANOVA revealed no group main effect, *F* (1, 26) = .79, $p = .38$, $\eta_p^2 = .03$. There was a significant main effect of Error, *F* (1, 26) = 4.61, $p = .04$, $\eta_p^2 = .15$. DT was significantly slower following an error (*M* = 885 ms, *SD* = 212) compared to an errorless trial (*M* = 867 ms, *SD* = 201), *p* = .04. There was also a significant Group x Error interaction, *F* (1, 26) = 5.26, $p = .03$, $\eta_p^2 = .17$. The random practice group had significantly slower DT following error compared to errorless trials, whereas the RStroop group showed no significant difference in DT following an error (*M* = 841 ms, *SD* = 195) compared to an errorless trial (*M* = 843 ms, *SD* = 188), *p* = 1.00, *d* = 0.01.

Stroop test

Response accuracy. Table 3 shows the mean RA on the Stroop test for the BStroop and RStroop groups across the three practice sessions. A 2 Group x 3 Practice ANOVA revealed no Group main effect, F (1, 26) = 1.23, p = .28, η_p^2 = .05. There was a Practice main effect, F (2, 52) = 4.48, p = .02, η_p^2 = .15. RA in practice 3 (M = 105, SD = 4) was significantly greater than in practice 1 (M = 104, SD = 4), p = .02, whereas RA in practice 2 (M = 105 ms, SD = 3) did not differ to pre-test and practice. No Group x Practice interaction occurred, F (2, 52) = .60, p = .55, η_p^2 = .02.

Decision time. Table 3 shows the mean DT in the Stroop test for the BStroop and RStroop groups across the three practice sessions. A 2 Group x 3 Practice ANOVA revealed no group main effect, F (1, 26) = .014, p = .91, η_p^2 < .01, no main effect for Practice, F (2, 52) = 1.30, p = .28, η_p^2 = .05, and no Group x Practice interaction, F (2, 52) = .01, p = .99, η_p^2 < .01.

Error analysis. Figure 7 shows mean DT for the BStroop and RStroop group in the secondary Stroop task following an error and an errorless trial across practice. A 2 Group x 2 Error ANOVA revealed no group main effect, F (1, 26) = .01, p = .91, η_p^2 < .01. There was a significant error main effect, F (1, 26) = 12.16, p < .01, η_p^2 = .32. DT was significantly slower following an error (M = 681 ms, SD = 87) compared to following an errorless trial (M = 664 ms, SD = 85), p < .01. There was also a significant Group x Error interaction, F (1, 26) = 4.25, p = .05, η_p^2 = .14. DT for the RStroop was significantly slower following an error (M = 687 ms, SD = 85) compared to an errorless trial (M = 661 ms, SD = 81), p < .01, d = 1.68. In comparison, DT for the BStroop group was not different following error (M = 674 ms, SD = 91) and errorless trials (M = 667 ms, SD = 91), p = .88, d = .21.

Discussion

As expected, for the two practice structure groups *without* the secondary task the traditional CI effect was found (Shea & Morgan, 1979). In the retention test, the random group was significantly more accurate compared to the blocked group, whereas in the pre-test there was no between-group difference in accuracy. With regards to the performance in the primary anticipation task for the two groups with the secondary Stroop test, no support was provided for either the elaboration hypothesis or the action plan reconstruction hypothesis. RA for the RStroop group in the retention test was not significantly different to the random group, suggesting that the participants were able to cope with the additional cognitive effort caused by the secondary task or they prioritized effort to maintain performance on the primary task at the cost of secondary task performance (Abernethy et al., 2007). Moreover, while the BStroop group were descriptively more accurate than the blocked group in the retention test as predicted and a significant interaction was found, the planned comparison did not reach significance. The suggestion is that the task did not cause a sufficient amount of forgetting, retrieval and reconstructive processes during practice compared to methods used in previous studies (Lin et al., 2008; 2010).

DT in the primary anticipation task was slower following an error compared to an errorless trial for the random group, but not for the other three groups. This finding suggests that following an error, greater cognitive effort is required using a random schedule of practice to generate an appropriate response compared to a blocked schedule of practice (Lam et al., 2010). However, contrary to predictions, DT in the primary anticipation task was not different between errorless and error responses for the RStroop group, suggesting that the secondary task affected the cognitive processes taking place. Performance on the Stroop task allowed for more of an insight into the effect of error processing on working memory for the RStroop and BStroop groups. The RStroop group had a slower RT in the Stroop test following an error compared to following an errorless trial. In comparison, RT for the BStroop group was not different following both errorless and error trials. It appears that performance decrements occurred on the secondary task for the RStroop group in order to maintain performance in the primary task. In contrast, the BStroop group could maintain performance in both the primary and secondary task due to lower cognitive demands of the primary task. The data show that this performance decrement in the secondary task for the RStroop group was not across every trial, but rather only following an error. This finding provides support for the alternative hypothesis that it is not just task switching that increases the load in working memory for the random group, but a combination of task switching in conjunction with error processing.

General Discussion

In this paper, we presented two experiments that examined the cognitive processes underlying the CI effect during the learning of anticipation judgments in tennis, specifically examining the role of error processing. In Experiment 1, we used a PRT task to measure cognitive effort in the observation and feedback phase of a trial during blocked and random practice. Cognitive effort was examined following errorless and error trials for blocked and random practice orders. In Experiment 2, we investigated the effects of inserting a cognitively demanding secondary task into the inter-trial interval of blocked and random practice, while again investigating the effects of errors on performance of the primary and secondary task.

Contextual interference effect and the underlying mechanisms

As predicted, in both experiments the anticipation accuracy of the random practice group was not different in the pre-test but significantly more accurate in the retention test when compared to the blocked group. Our findings support previous research on the CI effect in the motor skills literature (Shea & Morgan, 1979) and provide confirmation that the effect extends to perceptual-cognitive skills training (Broadbent et al. 2015a; Memmert et al., 2009). The data demonstrate the generalizability of the CI effect to perceptual-cognitive as well as perceptual-motor skills training, as the phenomenon has now been found to extend to skilled (Broadbent et al., 2015a) and novice participants using both complex movement responses (Broadbent et al., 2015a) and no movement responses. These findings indicate that a motor response may not be necessary to induce a CI effect; rather it is the cognitive processes that are key (Battig, 1972; Blandin, Proteau, & Alain, 1994). For decision time in the primary task, no differences were found between the two groups in any phase, contrary to previous research by Broadbent et al. (2015a). This contradictory finding is potentially due to the different tasks used in the two papers. Broadbent et al. (2015a) used a field-based transfer test with no temporal occlusion paradigm. In the current study, a laboratory-based setting was used and the footage was occluded around ball-racket contact. The temporal occlusion paradigm forces participants to respond to the footage earlier than they usually would, so a floor effect is found for the decision time data (Broadbent, Causer, Williams, & Ford, 2015b).

The two experiments examined the underlying cognitive mechanisms of the CI effect using the novel domain of perceptual-cognitive skills training. The majority of previous research has examined the CI effect using a motor task and debate still remains around the underlying mechanisms of this phenomenon. To provide further insight into the mechanisms involved, different secondary task protocols were used in the two experiments. These protocols enabled investigation of the cognitive effort involved at specific time points across an anticipation trial, examining both the elaborative processing hypothesis and the action plan reconstruction hypothesis (Magill & Hall, 1990).

Elaborative processing hypothesis. Support for the elaborative processing hypothesis was expected in a perceptual-cognitive skills task as the early work on the CI effect used a non-motor skill task to propose that inter-task comparisons were the source of interference in random practice (Battig, 1972; 1979). In Experiment 1, we showed that cognitive effort was greater in the feedback phase of a trial for a random compared to blocked schedule of practice. The feedback phase has previously been linked to the elaborative processing hypothesis as comparisons between trials can only occur once the participant is aware of the outcome of the trial (Li & Wright, 2000). This finding supports the elaborative processing hypothesis as the increased cognitive effort of the random group indicates that inter-task comparisons occurred in this practice condition but not in the blocked group (Shea & Zimny, 1983; 1988). However, the findings reported in Experiment 2 did not support the elaborative processing hypothesis. Inserting a cognitively demanding secondary task into the inter-trial interval did not affect learning in a random structure of practice, thereby contradicting previous research that has shown this effect (Lin et al., 2008). However, previously, researchers did not use a secondary task, but rather used TMS to disrupt elaborative processes (Lin et al., 2008; Lin et al., 2010). It may have been that the Stroop task was not disruptive enough to interfere with the between task comparisons taking place.

Action plan reconstruction hypothesis. While the elaborative processing hypothesis provides a plausible explanation for the acquisition of perceptual-cognitive skills, the action plan reconstruction hypothesis seems more precariously linked to this domain due to the idea that a motor program must be present in this process (Magill & Hall, 1990). The current data provided mixed support for this hypothesis. Experiment 2 provided only tentative evidence for the action plan reconstruction hypothesis. While the BStroop group did increase response accuracy in the retention test compared to the blocked group, this change did not reach conventional levels of significance. The suggestion is that the Stroop test may not have been as cognitively demanding as task switching and did not cause total forgetting of an action plan (Lee & Magill, 1983; 1985; Simon & Bjork, 2002). Alternatively, the Stroop task may have been too similar to the primary task, as both were perceptual in nature, and between-task similarity is negatively related to the CI effect (Boutin & Blandin, 2010).

In contrast, evidence from Experiment 1 supported the action plan reconstruction hypothesis and contradicts the notion that this hypothesis only applies to motor tasks

(Broadbent et al., 2015a; Carlson et al., 1989; Carlson & Yaure, 1988; Helsdingen et al., 2011a, 2011b). Greater cognitive effort was found in the observation phase of the trial for random compared to blocked practice. The observation phase has been linked to the action plan reconstruction hypothesis because an action plan can only be retrieved and reconstructed once participants are aware of the requirements of the upcoming task (Li & Wright, 2000). There are a few plausible explanations as to why the action plan reconstruction hypothesis is still applicable to a non-motor task. The evidence concerning *action anticipation* suggests that the motor system becomes activated through resonant mechanisms when observing an action (e.g., Aglioti et al., 2008). Therefore an action plan, as understood in the CI literature, is still implemented for the observed action. However, the current experiment used novice tennis player without a fine-tuned motor resonance system for the observed task, which suggests that this is not a fully valid argument (Broadbent et al., 2015). Alternatively, it may be that the definition and terminology currently used needs to be adjusted to acknowledge non-motor tasks. Previously, researchers have suggested that ‘strategies’ and ‘processing plans’ will still need to be retrieved and reconstructed similar to a motor program (Carlson & Yaure, 1988; Helsdingen et al., 2011a; 2011b). We propose that to provide an explanation consistent for both motor and non-motor tasks the terminology should be changed from the action plan reconstruction hypothesis to the *response plan reconstruction hypothesis*. As such, the definition for this hypothesis must state that for an upcoming task a person must retrieve and reformulate the appropriate *response plan* on each attempt as it has been forgotten by intervening responses. The individual under a random schedule of practice engages in more effortful reconstructive process to regenerate the *response plan* for subsequent performances.

Overall the current data showed some evidence for both the elaborative processing and action plan reconstruction hypothesis (Magill & Hall, 1990). Data from Experiment 1 indicate that elaborative and reconstructive processes occur in the observation and feedback phase, respectively. This finding suggests that the two hypotheses might not be viewed as being separate, but rather as an integrated hypothesis involving greater cognitive effort across the whole of the trial. In contrast, data from Experiment 2 examining the hypothesis led to null effects, suggesting an alternative hypothesis may have to be considered to explain this phenomenon.

Alternative hypothesis: Error processing

We investigated error processing as an additional explanation for the increased cognitive effort underlying random practice. Previously, researchers have suggested it is the switching of tasks that increases the load in working memory and underlies the learning benefits of random compared to blocked practice (Rendell et al., 2011). The current data provided some support for the proposal that task switching in conjunction with error processing underpins the CI effect. In Experiment 2, we demonstrated that RStroop group performance on the secondary task was negatively affected following an error compared to an errorless trial, supporting the error-processing hypothesis. Participants allocated more resources to the primary task on these trials to process errors in addition to the elaborative processing and response plan reconstruction caused by task switching. This finding shows some support for the idea that random practice increases the load in working memory similar to a secondary task and may create a form of implicit learning (Rendell et al., 2011). Moreover, in Experiment 2, support for the error-processing hypothesis was shown as the random group demonstrated slower decision times on the primary task following an error compared to an errorless trial, suggesting that the monitoring and controlling of a response increases following an error for the random, but not the blocked, practice group (Holroyd et al., 2005; Lam et al., 2010).

An alternative hypothesis is outlined combining ideas and concepts from the CI literature (Magill & Hall, 1990) and the error processing literature (Lam et al., 2010). The hypothesis suggests that error processing in conjunction with task switching may underpin the increased cognitive effort found for a random compared to blocked structure of practice. The greater cognitive effort following an error for a random schedule of practice could be due to participants having to both update the current rules for the previous task and store these (error processing), as well as retrieving the response plan for the upcoming task (reconstructive processes). The updating of responses would occur through inter- and intra-task comparisons (elaborative processing) made to identify discrepancies between the actual outcome and the desired goal (error processing). In contrast, following an error, a blocked structure of practice would not require the retrieval of a response plan (reconstructive processes) due to the repetitive nature of the trials, so would merely require the rules for the task to be updated (error processing) and this would not involve inter-task comparisons (elaborative processes), hence less cognitive effort would be required. This hypothesis is made tentatively and is to allow for clear hypotheses to be tested in future research to either support or contradict the potential role of error processing in the CI effect.

Conclusions

In this paper, we report two experiments that provided confirmation of the CI effect for the acquisition of perceptual-cognitive skills and some support for both the elaborative processing hypothesis and the newly termed response plan reconstruction hypothesis. Moreover, the experiments provide a novel insight into the role of error processing as a potential underlying mechanism in the CI effect. The current literature suggests that cognitive effort is greater for random practice compared to blocked practice due to task switching, specifically through elaborative and reconstructive processes. However, the current data further suggests that it may not be solely the switching of the tasks that underpins the CI effect, but error processing in conjunction with the task switching that causes greater cognitive effort for a random schedule of practice. In future, researchers should seek to examine error processing as an additional underlying mechanism of the CI effect. Furthermore, the extent to which task switching and error processing increase the load in working memory and potentially create a type of implicit learning should be examined (Rendell et al., 2010). The CI effect has been shown to extend to a range of domains and conditions from simple motor skill tasks with novice participants (e.g., Shea & Morgan, 1979) to complex sporting tasks with expert athletes (e.g., Hall, Domingues, & Cavazos, 1994). Further research is required to assess the role of error processing in conjunction with task switching in a variety of domains and conditions to determine the generalizability of the alternative theory proposed in this paper.

References

Abernethy, B., Maxwell, J. P., Masters, R. S., van der Kamp, J., & Jackson, R. C. (2007). Attentional processes in skill learning and expert performance. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of Sport Psychology* (pp. 245-263). Hoboken, New Jersey: John Wiley & Sons, Inc.

Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience, 11*, 1109-1116.

Battig, W. F. (1972). Intratask interference as a source of facilitation in transfer and retention. In R. F. Thompson & J. F. Voss (Eds.), *Topics in learning and performance*. New York: Academic Press.

Battig, W. F. (1979). The flexibility of human memory. In L. S. Cermak & F. I. M. Craik (Eds.), *Levels of processing in human memory* (pp. 23-44). NJ: Erlbaum: Hillsdale.

Blandin, Y., Proteau, L., & Alain, C. (1994). On the cognitive processes underlying contextual interference and observational learning. *Journal of Motor Behavior*, *26*, 18-26.

Boutin, A., & Blandin, Y. (2010). Cognitive underpinnings of contextual interference during motor learning. *Acta psychologica*, *135*, 233-239.

Brady, F. (1998). A theoretical and empirical review of the contextual interference effect and the learning of motor skills. *Quest, 50*, 266-193.

Brady, F. (2008). The contextual interference effect and sport skills. *Perceptual and Motor Skills, 106*, 461-472.

Broadbent, D. P., Causer, J., Ford, P. R., & Williams, A. M. (2015a). Contextual interference effect in perceptual–cognitive skills training. *Medicine & Science in Sports & Exercise*, *47*, 1243-1250.

Broadbent, D. P., Causer, J., Williams, A. M., & Ford, P. R. (2015b). Perceptual-cognitive skill training and its transfer to expert performance in the field: Future research directions. *European Journal of Sport Science, 15*, 322-331.

Carlson, R.A. & Yaure, R.C. (1988). *Random access of component skills in acquisition and problem solving.* Paper presented at annual meeting of the Psychonomic Society, Chicago, IL.

Carlson, R.A., Sullivan, M.A. & Schneider, W. (1989). Practice and working memory effects in building procedural skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 517-526.

Cross, E. S., Schmitt, P. J., & Grafton, S. T. (2007). Neural substrates of contextual interference during motor learning support a model of active preparation. *Journal of Cognitive Neuroscience, 19*, 1854-1871.

Denis, D., Rowe, R., Williams, A. M., & Milne, E. (2016). The role of cortical sensorimotor oscillations in action anticipation. *NeuroImage*, doi10.1016/j.neuroimage.2016.10.022

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102*, 211-245.

Goode, S., & Magill, R.A. (1986). Contextual interference effects in learning three badminton serves. *Research Quarterly for Exercise and Sport, 57*, 308-314.

Goh, H. T., Gordon, J., Sullivan, K. J., & Winstein, C. J. (2014). Evaluation of attentional demands during motor learning: Validity of a dual-task probe paradigm. *Journal of Motor Behavior, 46,* 95-105.

Hall, K. G., Domingues, D. A., & Cavazos, R. (1994). Contextual interference effects with skilled baseball players. *Perceptual Motor Skills, 78*, 835-841.

Helsdingen, A., van Gog, T., & van Merriënboer, J. (2011a). The effects of practice schedule and critical thinking prompts on learning and transfer of a complex judgment task. *Journal Educational Psychology, 103*, 383-398.

Helsdingen, A., van Gog, T., & van Merriënboer, J. (2011b). The effects of practice schedule on learning a complex judgment task. *Learning and Instruction, 21*, 126-136.

Holroyd, C. B., Yeung, N., Coles, M. G. H., & Cohen, J. D. (2005). A mechanism for error detection in speeded response time tasks. *Journal of Experimental Psychology: General, 134*, 163-191.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132,* 47-70.

Kilner, J. M., Vargas, C., Duval, S., Blakemore, S. J., & Sirigu, A. (2004). Motor activation prior to observation of a predicted movement. *Nature Neuroscience, 7*, 1299-1301.

Koehn, J. D., Dickinson, J., & Goodman, D. (2008). Cognitive demands of error processing. *Psychological Reports*, *102*, 532-538.

Lam, W. K., Masters, R. S., & Maxwell, J. P. (2010). Cognitive demands of error processing associated with preparation and execution of a motor skill. *Consciousness and Cognition, 19*, 1058-1061.

Lee, T. D. (2012). Contextual interference: Generalizability and limitations. In N. J. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport: Research, theory and practice* (pp. 79-93). New York: Routledge.

Lee, T. D., & Magill, R. A. (1983). The locus of contextual interference in motor-skill acquisition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9*, 730-746.

Lee, T. D., & Magill, R. A. (1985). Can forgetting facilitate skill acquisition. In D. Goodman, R. B. Wilberg, & I. M. Franks (Eds.), *Differing perspectives in motor learning and control* (pp. 3-22). Amsterdam, North Holland: Elsevier.

Lee, T. D., Magill, R. A., & Weeks, D. J. (1985). Influence of practice schedule on testing schema theory predictions in adults *Journal of Motor Behavior, 17,* 283-299.

Lee, T. D., Swinnen, S. P., & Serrien, D. J. (1994). Cognitive effort and motor learning. *Quest, 46*, 328-344.

Lee, T. D., Wishart, L. R., Cunningham, S., & Carnahan, H. (1997). Modelled timing information during random practice eliminates the contextual interference effect. *Research Quarterly for Exercise and Sport, 68*, 100-105.

Lee, T. D., Wulf, G., & Schmidt, R. A. (1992). Contextual interference in motor learning – Dissociated effects due to the nature of task variations. *Quarterly Journal of Experimental Psychology, 44,* 627-644.

Li, Y., & Wright, D. L. (2000). An assessment of the attention demands during random- and blocked-practice schedules *The Quarterly Journal of Experimental Psychology, 53A,* 591-606.

Lin, C-H., Fisher, B. E., Winstein, C. J., Wu, A. D., & Gordon, J. (2008). Contextual interference effect: Elaborative processing or forgetting-reconstruction? A post hoc analysis of transcranial magnetic stimulation-induced effects on motor learning. *Journal of Motor Behavior, 40*, 578-586.

Lin, CH., Fisher, B. E., Wu, A. D., Ko, Y-A., Lee, L-Y., & Winstein, C. J. (2009). Neural correlate of the contextual interference effect in motor learning: A kinematic analysis. *Journal of Motor Behavior, 41*, 232-242.

Lin, C-H., Winstein, C. J., Fisher, B. E., & Wu, A. D. (2010). Neural correlates of the contextual interference effect in motor learning: A transcranial magnetic stimulation investigation. *Journal of Motor Behavior, 42*, 223-232.

Long, D. L., & Prat, C. S. (2002). Working memory and Stroop interference: An individual differences investigation. *Memory & Cognition, 30*, 294-301.

Macleod, C. M. (1991). Half a century of research on the Stroop Effect: An integrative review. *Psychological Bulletin, 109*, 163-203.

Macleod, C. M. (1992). The Stroop Task - the gold standard of attentional measures. *Journal of Experimental Psychology: General, 121*, 12-14.

Magill, R. A., & Hall, K. G. (1990). A review of the contextual interference effect in motor skill acquisition. *Human Movement Science, 9*, 241-289.

Magnuson, C. E., & Wright, D. L. (2004). Random practice can facilitate the learning of tasks that have different relative time structures. *Research Quarterly for Exercise and Sport, 75*, 197-202.

Maxwell, J. P., Masters, R. S., Kerr, E., & Weedon, E. (2001). The implicit benefit of learning without errors. *The Quarterly Journal of Experimental Psychology, 54*, 1049-1068.

Memmert, D., Hagemann, N., Althoetmar, R., Geppert, S., & Seiler, D. (2009). Conditions of practice in perceptual skill learning. *Research Quarterly for Exercise and Sport, 80,* 32-43.

Merbah, S., & Meulemans, T. (2011). Learning a motor skill: Effects of blocked versus random practice a review. *Psychologica Belgica, 51*, 15-48.

Ollis, S., Button, C., & Fairweather, M. (2005). The influence of professional expertise and task complexity upon the potency of the contextual interference effect. *Acta Psychologica, 118*, 229-244.

Pauwels, L., Swinnen, S. P., & Beets, I. A. M. (2014). Contextual interference in complex bimanual skill learning leads to better skill persistence. *Plos One, 9*(6): e100906. doi:10.1371/journal.pone.0100906.

Rabbitt, P. M. (1966). Error and error correction in choice-response tasks. *Journal of Experimental Psychology, 71*, 264-272.

Rabbitt, P. M. (1967). Time to detect errors as a function of factors affecting choice-response time. *Acta Psychologica*, *27*, 131-142.

Rendell, M. A., Masters, R. S., Farrow, D., & Morris, T. (2010). An implicit basis for the retention benefits of random practice. *Journal of Motor Behavior, 43,* 1-13.

Salmoni, A. W., Sullivan, J. J., & Starkes, J. L. (1976). The attentional demands of movement: A critique of the probe technique. *Journal of Motor Behavior, 8*, 161-169.

Shea, J. B., & Morgan, R. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 179-187.

Shea, J. B., & Titzer, R. C. (1993). The influence of reminder trials on contextual interference effects. *Journal of Motor Behavior, 25*, 264-274.

Shea, J. B., & Zimny, S. T. (1983). Context effects in memory and learning information. In R. A. Magill (Ed.), *Memory and control of action* (pp. 345-366). Amsterdam: North Holland.

Shea, J. B., & Zimny, S. T. (1988). Knowledge incorporation in motor presentation In O. G. Meijer & K. Roth (Eds.), *Advances in psychology* (pp. 289-314). Amsterdam, Netherlands: Elsevier Science Publishers

Simon, D. A., & Bjork, R. A. (2002). Models of performance in learning multisegment movement tasks: Consequences for acquisition, retention, and judgments of learning. *Journal of Experimental Psychology: Applied, 8,* 222-232.

Smith, P. J. K., & Davies, M. (1995). Applying contextual interference to the Pawlata roll. *Journal of Sport Sciences, 13*, 455-462.

Wright, D. L. (1991). The role of intertask and intratask processing in acquisition and retention of motor skills. *Journal of Motor Behavior, 23,* 139-145.

Wright, D. L., Magnuson, C. E., & Black, C. B. (2005). Programming and reprogramming sequence timing following high and low contextual interference practice. *Research Quarterly for Exercise and Sport, 76*, 258-266.

Wright, D. L., Li, Y., & Whitacre, C. (1992). The contribution of elaborative processing to the contextual interference effect. *Research Quarterly for Exercise and Sport, 63*, 30-37.

Wright, D. L., Verwey, W., Buchanan, J., Chen, J. Rhee, J., & Immink, M. (2015). Consolidating behavioural and neurophysiologic findings to explain the influence of contextual interference during motor sequence learning. *Psychonomic Bulletin & Review,* doi:10.3758/s13423-015-0887-3.

Wulf, G., McNevin, N. H., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *Quarterly Journal of Experimental Psychology, 54A*, 1143-1154.

Table Captions

Table 1. Experiment 1: Mean (SD) decision time (ms) in the primary anticipation task for the Blocked and Random groups across the pre-test, practice, and retention test.

Table 2. Experiment 1: Mean (SD) decision time (ms) in the primary anticipation task, and mean (SD) reaction time (ms) in the secondary task, for the Blocked and Random groups on errorless and error responses in the previous trial.

Table 3. Experiment 2: Mean (SD) response accuracy (number of correct trials) and decision time (ms) in the Stroop test for the BStroop and RStroop groups across the three practice sessions.

Figure Captions

Figure 1. The experimental set up.

Figure 2. The experimental design and layout of an individual trial for (a) Experiment 1 and (b) Experiment 2.

Figure 3. Experiment 1: Mean (SD) response accuracy (%) in the primary anticipation task for the Blocked and Random group in the pre-test, practice, and retention test. *$p < .05$

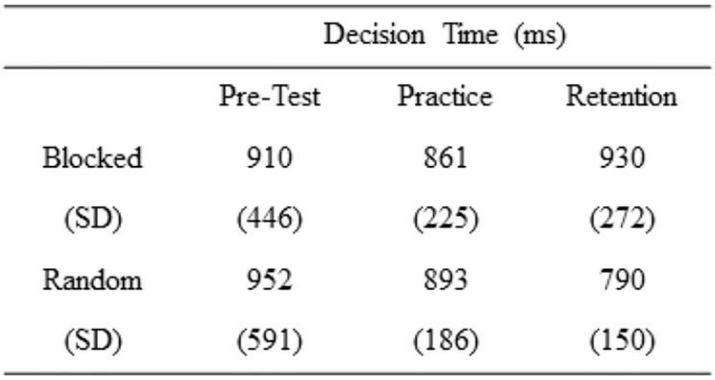
Figure 4. Experiment 1: Mean (SD) response time (ms) for the probe reaction time (PRT) for the Blocked and Random group in tone only, observation phase, and feedback phase. *$p < .05$

Figure 5. Experiment 2: Mean (SD) response accuracy (number of correct trials) in the primary anticipation task for the Blocked, Random, BStroop, and RStroop groups in the pre-test, practice, and retention test. *$p < .05$

Figure 6. Experiment 2: Mean (SD) decision time (ms) in the primary anticipation task for the Blocked, BStroop, Random group and RStroop groups following error and errorless trials. *$p < .05$

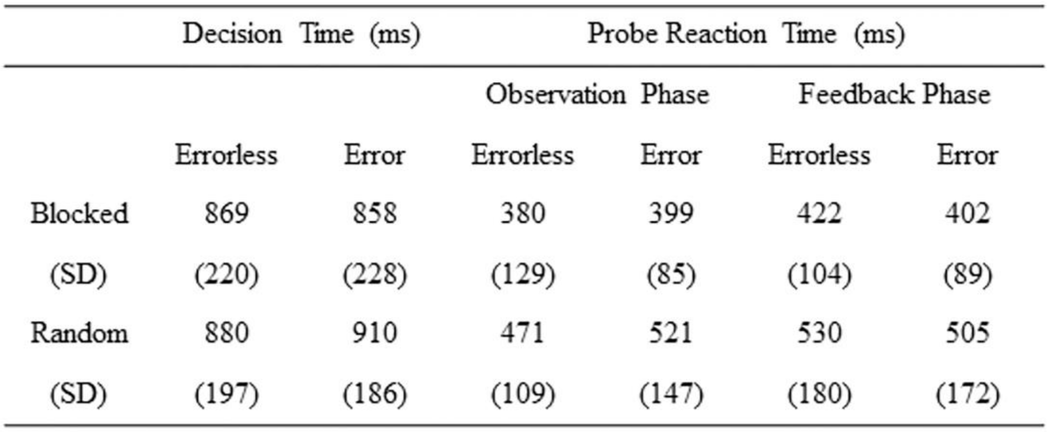
Figure 7. Experiment 2: Mean (SD) decision time (ms) in the secondary Stroop task BStroop and RStroop groups following error and errorless trials for the. *$p < .05$

Table 1.



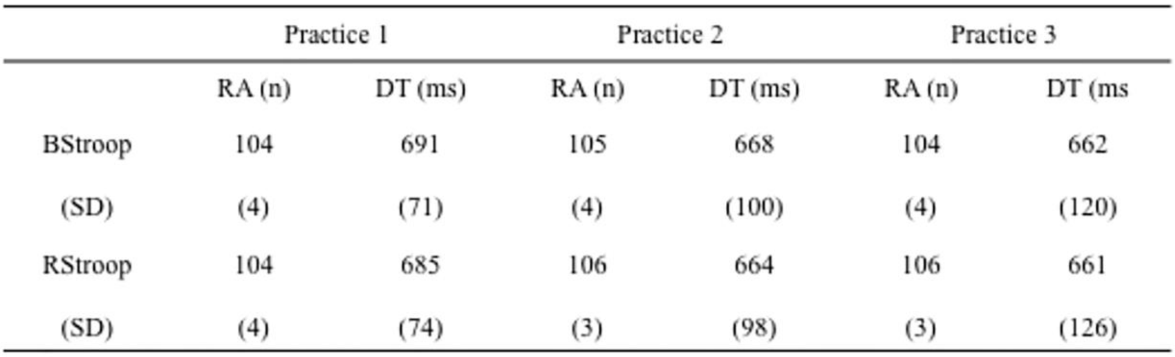
	Decision Time (ms)		
	Pre-Test	Practice	Retention
Blocked	910	861	930
(SD)	(446)	(225)	(272)
Random	952	893	790
(SD)	(591)	(186)	(150)

Table 2.



	Decision Time (ms)		Probe Reaction Time (ms)			
			Observation Phase		Feedback Phase	
	Errorless	Error	Errorless	Error	Errorless	Error
Blocked	869	858	380	399	422	402
(SD)	(220)	(228)	(129)	(85)	(104)	(89)
Random	880	910	471	521	530	505
(SD)	(197)	(186)	(109)	(147)	(180)	(172)

Table 3.



	Practice 1		Practice 2		Practice 3	
	RA (n)	DT (ms)	RA (n)	DT (ms)	RA (n)	DT (ms
BStroop	104	691	105	668	104	662
(SD)	(4)	(71)	(4)	(100)	(4)	(120)
RStroop	104	685	106	664	106	661
(SD)	(4)	(74)	(3)	(98)	(3)	(126)

1034 Figure 1.

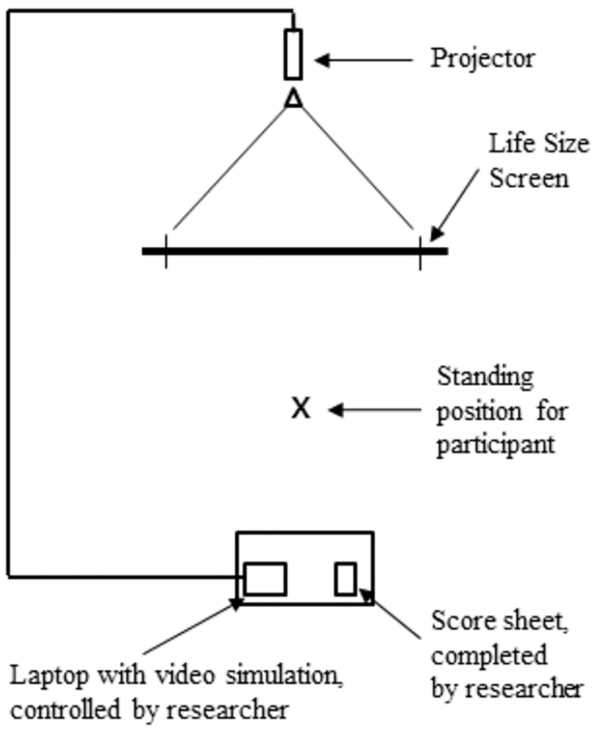
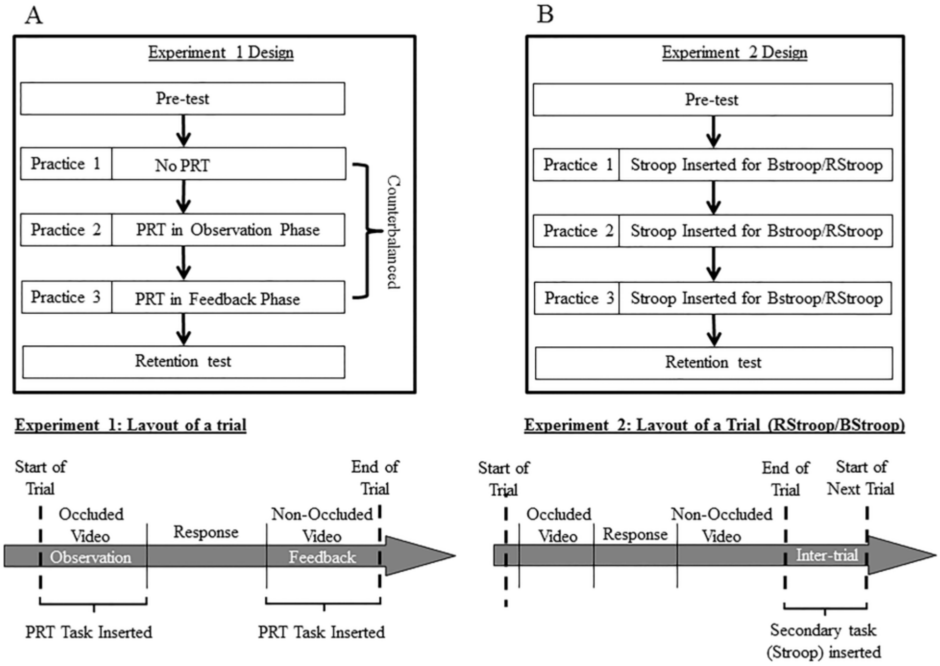
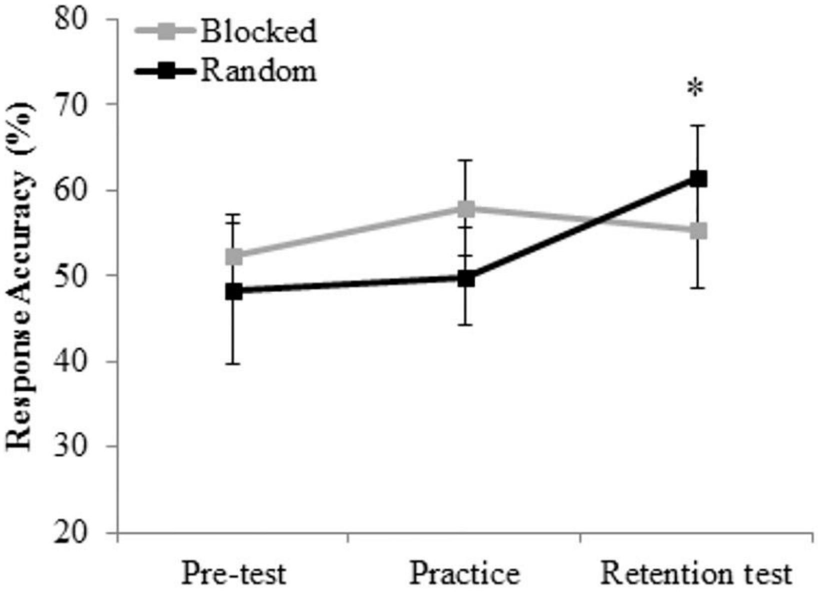


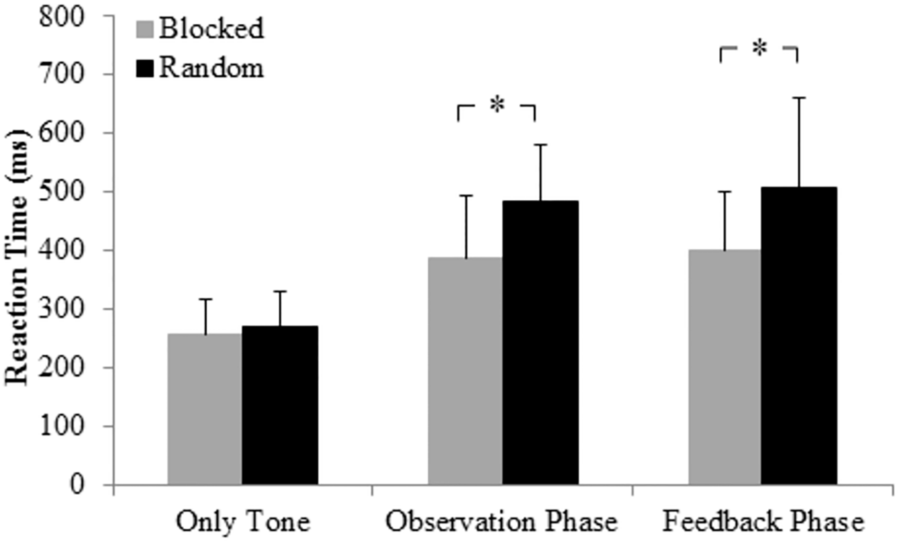
Figure 2


A
Experiment 1 Design
Pre-test
Practice 1
No PRT
Practice 2
PRT in Observation Phase
Practice 3
PRT in Feedback Phase
Counterbalanced
Retention test
B
Experiment 2 Design
Pre-test
Practice 1
Stroop Inserted for Bstroop/RStroop
Practice 2
Stroop Inserted for Bstroop/RStroop
Practice 3
Stroop Inserted for Bstroop/RStroop
Retention test
Experiment 1: Layout of a trial
Start of Trial
End of Trial
Occluded Video
Response
Non-Occluded Video
Observation
Feedback
PRT Task Inserted
PRT Task Inserted
Experiment 2: Layout of a Trial (RStroop/BStroop)
Start of Trial
End of Trial
Start of Next Trial
Occluded Video
Response
Non-Occluded Video
Inter-trial
Secondary task (Stroop) inserted

1036 Figure 3.



1038 Figure 4.



1040 Figure 5.

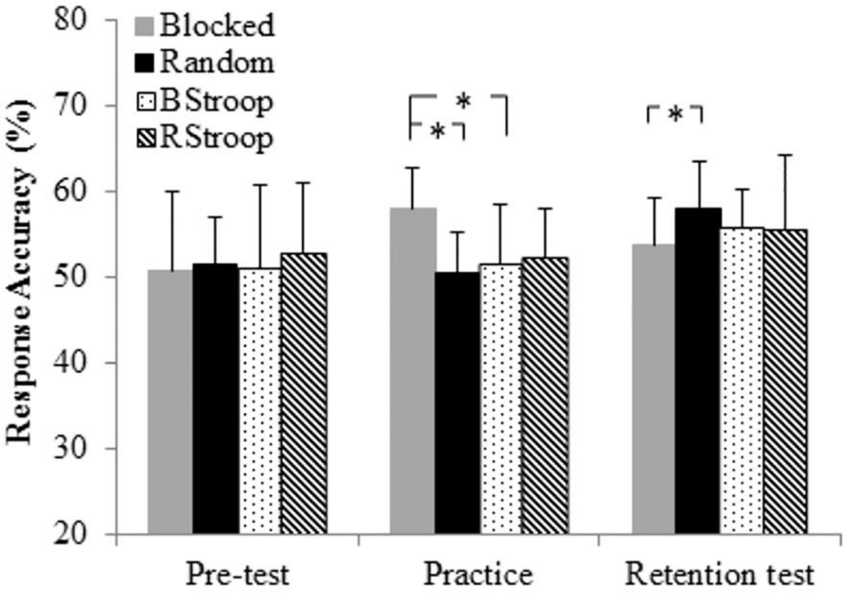
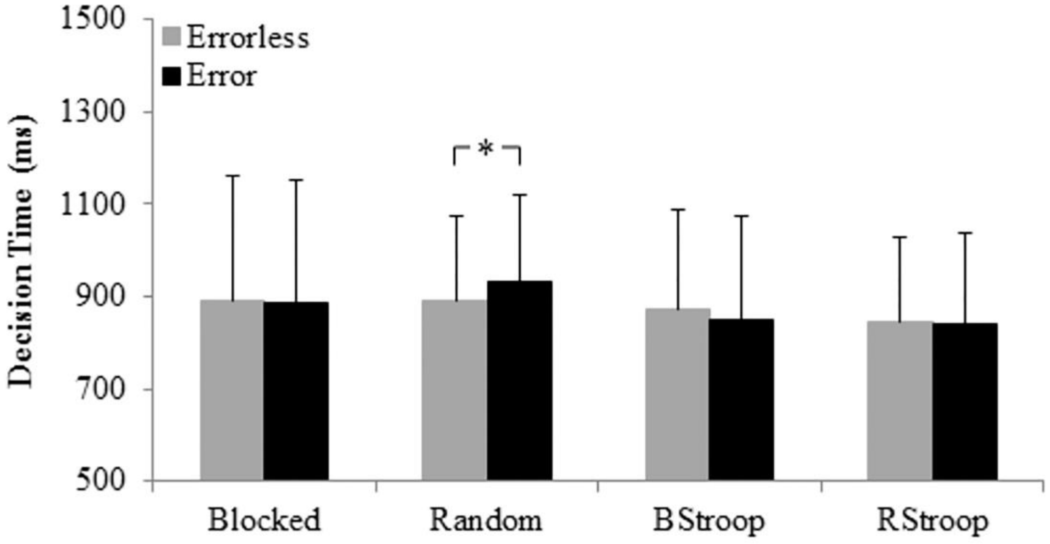


Figure 6.


Decision Time (ms)
1500
1300
1100
900
700
500
Errorless
Error
*
Blocked
Random
BStroop
RStroop

1043 Figure 7.