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The Effect on Response Complexity on Task-switching Behaviour

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The Effect on Response Complexity on Task-switching Behaviour

by

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Bachelor of Arts, Brock University, 2006

THESIS

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Abstract

Research on task-switching has shown that when participants are asked to switch between two different tasks, they are slower than when they repeat the same task. These costs have also been shown to increase when the previous response is repeated; however, very little has been done to investigate the role of response complexity in this relationship. We manipulated response complexity by increasing both the number of stimulus-response pairs and the number of individual response components. We hypothesized that increased response complexity would increase both the switch costs and the response repetition effect. Results indicated that increasing the number of S-R pairs increased subsequent switch costs, but only during certain contexts. We also determined that increasing the number of individual response components increased the response repetition effect, suggesting that more response inhibition occurred when more response components were needed. Taken together, these findings provide evidence that response complexity impacts task-switching behaviour.

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Task-Switching and Response Complexity

Interacting with our daily environment requires one to repeatedly and often rapidly switch between tasks; a behaviour that requires some amount of cognitive flexibility. The *task-switching paradigm* has provided researchers with an accurate and efficient method to investigate the cognitive flexibility needed during task-switches. Introduced by Jerslid (1927), the task-switching paradigm requires participants to repeatedly switch between two tasks. The mean response time (RT) during these task-switches is then compared to the RT obtained when participants repeated the same task, and a *task-switch cost* is almost always incurred (e.g., Allport, Styles & Hsieh, 1994; Jerslid, 1927; Rogers & Monsell, 1995). Moreover, this switch cost is found with a number of variations of the task-switch paradigm (e.g., Jersild, 1927; Meiran, 1996; Rogers & Monsell, 1995).

In the initial investigations, researchers presented task repetitions in pure lists, that is lists which required only one task to be performed, while task switches were presented in mixed lists, in which tasks were presented in an ABAB format (Allport et al., 1994; Jersild, 1927); however, these methods were criticized for their inability to differentiate between switch costs and costs of keeping more than one task active in working memory (Rogers & Monsell, 1995). Thus, more recent investigations have implemented two new variations of the task-switching paradigm. Specifically, Rogers and Monsell, introduced an *alternating runs* paradigm in which participants performed tasks in an AABB pattern. This design allows researchers to measure task-switch and task-repeat response times while two different task-sets are kept active in working memory, resolving the confound in the previous literature. Other researchers have also put forth a random task presentation format, in which participants are unaware of which task they will be performing until they are cued on the current trial (Meiran, 1996; Phillip, Jolicoeur, Falkenstein & Koch, 2007). It is this methodology that will be used in the current research.

Along with these methodological variations, researchers also are unable to agree on the cognitive processes involved in the production of switch costs. While several models have been presented, they all fall into one of two theoretical categories. One category finds its basis in the realm of priming, proactive interference and inhibition. Specifically, these models suggest that the context of the previous trial can proactively interfere with the current trial by inhibiting the relevant task or priming irrelevant responses, and it is the time needed to overcome this task irrelevant information that produces switch costs (Allport et al., 1994; Gilbert & Shallice, 2002; Schneider & Logan, 2005; Steinhauser & Hubner, 2006; Waszak, Hommel & Allport, 2003; Wylie & Allport, 2000). In contrast, other researchers have proposed that switch costs are not the result of passive activation and inhibition, but are instead the result of executive control processes, which allow the successful reconfiguration of task-sets (Meiran, 1996, 2000; Rogers & Monsell, 1995; Rubinstein, Meyers & Evans, 2001). Both of these ideas will be discussed in the next sections.

Priming Models of Task-Switching

As mentioned above, many researchers have found evidence that switch costs stem from the activation of the now-irrelevant information from the previous trial. In early investigations of this hypothesis, Allport and colleagues (1994) suggested a possible *proactive interference* effect as the source of the switch costs. They proposed that the task activations and inhibitions from the previous trial resulted in interference during the current trial, producing switch costs. Specifically, they found that during a Stroop task-switch paradigm participants produced substantial switch costs when switching from the Colour-naming task to the Word-naming task;

however, these costs disappeared when participants switched from the Word-naming task to the Colour-naming task. Consequently, Allport et al., (1994) suggested that because the participants were more familiar with reading words compared to naming their colours, they only had to increase the task activation for the less dominant Colour-naming task, and not the Word-naming task, in order to perform it successfully. This increased activation was achieved by suppressing the more dominant Word-naming task, which negatively primed it in the succeeding trials, slowing responses and producing switch costs. It should be noted that switch costs have since been found when participants are required to switch from the Stroop Word-naming task to the Stroop Colour-naming task (Wylie & Allport, 2000); however, these costs are much less than those found by Allport et al., (1994), suggesting that task dominance is a key factor in the production of switch costs.

Results have also shown that when participants were asked to switch from Colour Word-naming to Digit-naming they were slower to respond if the presented stimulus had been previously associated with a task switch from Ink Colour-naming to Group-size naming (Allport et al., 1994). It was also found that these increased switch costs persisted for up to one or two minutes, increasing the response times for as many as nine task-switch and task-repeat trials (Allport et al., 1994). Interestingly, when participants were allowed a large preparatory interval of 1100ms prior to a task-switch, only a small decrease in switch costs occurred. Each of these findings led Allport and his colleagues (1994) to suggest a *Task-Set Inertia Model* of task-switching. According to the model, switch costs stem from a proactive interference from the previous trial caused by the suppression of the dominant task. This suppression must then be overcome in the subsequent task-switch trial in order for a response to be successfully and correctly executed. Given that this suppression takes time to decay, costs are not limited to the immediate task-switch trial, increasing response times for subsequent repetitions of the suppressed task. Furthermore, switch costs are not resolved by substantial preparatory intervals; however, they can be slightly decreased given that the suppression does decay over time.

While the initial proposal of the Task-Set Inertia model offered a foundation from which researchers could build, more recent investigations have brought forth some new findings as well as changes to the original ideas of Allport and his colleagues (1994 - Wylie & Allport, 2000). In further tests of the Task-Set Inertia Model, Wylie and Allport (2000) looked at the roles of both the previous and current trials to determine if it indeed was proactive interference that produced residual switch costs. Participants were asked to switch from a neutral colour-naming task (coloured x's) to both a neutral Word-naming task (words presented in black ink) and a Stroop Word-naming task (All-Neutral and Colour-Neutral Conditions respectively). According to the Task-Set Inertia model, switch costs stem from the suppression of the dominant task during the previous trial. Given that the neutral colour-naming stimuli cannot activate the Word-naming task, no suppression should be required. As a result, it was hypothesized that switch costs would be the same regardless of whether or not the participants switched to a neutral or Stroop Word-naming task; however, if switch costs were the product of switching to a specific task, then it was expected that switch costs would be larger for the Stroop Word-naming task compared to the Neutral Word-naming task. Results showed that switch costs did not differ between the All-Neutral and Colour-Neutral conditions, suggesting that it was not the switch to the Stroop Word-naming task but the switch from the Stroop colour-naming task that produced the substantial switch costs in Allport et al. (1994).

To further support this finding, Wylie and Allport (2000) also had participants switch between a Stroop Colour-naming task and a Stroop Word-naming task (All-Stroop Condition) and compared their response times to those obtained in the Colour-Neutral condition outlined above. They hypothesized that the Stroop Colour-naming task would require the suppression of the Word-naming task in order for the correct response to be executed. Consequently, switch costs should be larger in the All-Stroop condition compared to the Colour-Neutral condition, which did not require the suppression of the Word-naming task. Indeed, results supported this hypothesis, providing further evidence that switch costs stemmed from a proactive interference of the previous trial as suggested by the Task-Set Inertia Model of Allport and colleagues (1994).

Yet the model was unable to account for all of the results from Wylie and Allport (2000). For instance, if the Task-Set Inertia model were correct, as the number of trials between the interference trial and the current trial increases, the amount of suppression for the current task should decrease, producing smaller RTs at equal increments (Allport et al., 1994); however, the results of Wylie and Allport (2000) did not support this prediction. In a second experiment, participants were asked to perform an alternating series of All Stroop and Colour Neutral task blocks with each block containing 6 four trial cycles (two colour-task trials, two word-task trials). If the Task-Set Inertia model were correct, it was expected that the interference from Colour-naming trials in the All Stroop block should decrease monotonically as the number of completed cycles in the Colour Neutral block increased. In other words, in the Colour Neutral block (following the All Stroop block), the RTs on word-naming switch trials during Cycle 3-4 should not be significantly different than the RTs on word-naming repetition trials during Cycle 1-2, given that the suppression of the Stroop Word-naming task from the All-Stroop block has continually decreased and no more suppression is needed to perform the Neutral Colour-naming task.

Overall, results supported the Task-Set Inertia model and illustrated a significant decrease in response times across the six cycles of the Colour Neutral block (Wylie & Allport, 2000); however, the predicted monotonic pattern of this decrease was not supported. In particular, Wylie and Allport (2000) found that RTs on Word-naming switch trials were significantly larger than the RTs on the previous Word-naming repetition trial. They hypothesized that this increase in RT was due to a reoccurrence of the proactive interference produced by a learned item-specific task association. Indeed, many of the Stroop Word-naming stimuli had been previously presented as distractors during the Stroop Colour-naming task in the All Stroop block, creating specific episodic memory traces for each individual stimulus. Consequently, when these stimuli were presented again during a switch to the Stroop Word-naming task in the Colour-Neutral block, the proactive interference was re-elicited.

Evidence for this hypothesis comes from previous work in which Allport and Wylie (1999) found that proactive interference was significantly increased when the same Stroop Word-naming stimuli were presented as distractors during the Stroop Colour-naming task. Follow-up studies from Wylie and Allport (2000) also provided further evidence by increasing the stimulus presentation ratio for the Stroop Colour-naming task and the Stroop Word-naming Task from 1:2 in Experiment 2 (above) to 2:1 in Experiment 3 respectively. Results showed that when participants were given more opportunities to learn item-specific associations during the Stroop Colour-naming task, the costs incurred following a switch to the Stroop Word-naming task were significantly increased. Taken together with all of their other findings, Wylie and Allport (2000) proposed that changes needed to be made to the initial ideas of the Task-Set Inertia model and suggested that a *Stimulus-Cue Retrieval model* may be a better candidate to explain the processes involved in task-switching.

The introduction of the Stimulus-Cue Retrieval model brought the focus of the literature away from stimulus-task interference and redirected it toward stimulus-response interference. As outlined by Wylie and Allport (2000) and their model, when a presented stimulus was previously associated with a different task, the learned stimulus-response (S-R) associations for that previous task are elicited. It is these S-R associations and not the task itself that must be suppressed. As suggested above, the Stimulus-Cue Retrieval model provides a reasonable explanation for the results of Wylie and Allport (2000) as well as Allport and Wylie (1999). Furthermore, by replicating the earlier work of Allport et al. (1994), Wylie and Allport (2000) were able to apply their model to previous investigations of task-switching as well, arguing against the task suppression hypothesis of switch costs in support for their stimulus-response association hypothesis.

More recent investigations have provided additional evidence that S-R activations play a key role in the production of switch costs. In a study by Steinhauser and Hubner (2006), incorrect responses were evaluated on the basis of their source (i.e., task confusion or response confusion). It was hypothesized that while response confusion would lead to an incorrect response, it would still produce S-R associations for the trial relevant task; however, if the incorrect response was due to task confusion, then S-R associations would be made with the trial irrelevant task, producing switch benefits instead of switch costs on the subsequent trial. Indeed results supported this hypothesis and it was found that, in instances of task confusion, incorrect responses resulted in task-switch benefits and task-repetition costs. In other words, it appeared that when Task A was incorrectly performed as Task B on the previous trial, the S-R associations for that trial were also incorrectly associated with Task B. Consequently, the supposed 'switch' to Task B on the following trial became a task repeat and thus, the S-R associations of the previous trial enhanced performance and produced a switch benefit instead of the expected switch cost.

These findings also provided evidence against a task activation (and suppression) model of task-switching similar to that suggested by Allport et al.'s (1994) Task-Set Inertia model. As previously mentioned, the Task-Set Inertia model suggests that task-switching costs are produced by an activation of the irrelevant task and suppression of the relevant task on the current trial. Thus, if we consider the idea that error detection requires that the relevant task become activated during the post-response error detection processes (consequently suppressing the competing irrelevant task), we would expect that this post-response task activation alone would lead to switch costs in the following trial; however, results do not support this hypothesis.

In investigations of error detection, Steinhauser and Hubner (2006) found that error awareness did not change the switch benefits recorded following erroneous responses. They found that only when the participants actually corrected the error and produced the correct response did the benefits become costs during the subsequent switch trial. These findings argue against an activation account of task-switching and instead provide support for a response-based strengthening account, similar to the Stimulus-Cue Retrieval Model of Wylie and Allport (2000). Based on this account, Steinhauser and Hubner (2006) suggested that task-switching costs stem from the binding of a specific S-R pair to a particular task context. Thus, when incorrect responses are made due to task-confusion, the S-R pair becomes incorrectly associated with the other task, producing benefits on the subsequent 'switch' trial. Furthermore, Steinhauser and Hubner (2006) emphasized the importance of response production in re-mapping the S-R associations. Consequently, it is only when an erroneous response is physically corrected that the

S-R pairs become associated with the correct task, producing the expected switch costs on the following switch trial.

Further support for a stimulus-response association account was provided by Waszak et al. (2003). In a variation from the tasks presented by Wylie and Allport (2000) and Allport and colleagues (1994), participants for Waszak et al. (2003) were asked to perform alternating word-naming and picture-naming task in response to incongruent picture-word stimuli (i.e., object picture with a word super imposed onto it). Like the findings of Wylie and Allport (2000), results showed that when compared to baseline trials, individuals produced larger switch costs when asked to perform the Word-naming task on stimuli that were previously presented in the picture-naming task. This interference was also found to be long lasting with priming effects occurring even after a 100 trial lag (Waszak et al., 2003). Similar findings were also found when participants were asked to name the pictures in response to stimuli that were previously presented for the word-naming task. In both experimental instances, switch costs were found even after a preparation interval was provided, offering additional evidence that residual switch costs result from item-specific priming effects from previous trials.

In a further replication of Wylie and Allport (2000), Waszak and colleagues (2003) were also able to manipulate the strength of the S-R associations by increasing the number of previous stimulus-task presentations prior to the task switch. Again, they found that as the number of previous stimulus-task presentations increased, so did the switch costs. As a result of their findings, Waszak et al. (2003), like others, suggested that switch costs stem from a stimulus-cued activation from the previous trial in which the current stimulus triggers a retrieval of the S-R associations with the now irrelevant tasks.

In spite of this, the results from Waszak and colleagues (2003) were not completely supported by the previous models of stimulus-response association. In particular, results indicated that increased switch costs were found even when the S-R mappings remained the same between tasks (i.e., congruent responses). According to the stimulus-response association accounts described above, this result should not occur given that the S-R associations for the current trial match the S-R associations for the previous trial and thus would not need to be suppressed. Therefore, these results suggest that the increase in switch costs is the result of a stimulus-task binding and not a stimulus-response binding as suggested by Wylie and Allport (2000) and Steinhauser and Hubner (2006). As you may recall, the role of task activation was previously outlined in Allport et al.'s (1994) Task-Set Inertia model. Using this model and their own data as a foundation, Waszak, Hommel and Allport (2005) tested two different priming effects: Negative Priming and Competitor Priming.

Originally suggested by Allport and colleagues (1994), a negative priming hypothesis suggests that when an individual must switch between performing two task (Task A and Task B), they must suppress the irrelevant task in order to correctly perform the relevant task on the current trial. It is hypothesized that when a task must be suppressed, an episodic memory trace is created and is later recalled when the same task is presented in subsequent trials. Consequently, when the to-be-ignored task must be attended to, an increase in switch costs occur; however, if the to-be-ignored task must again be ignored, as in task repeat trials, the response is faster (Waszak et al., 2005). On the other hand, competitor priming supports a stimulus-cue retrieval model of task-switching. Accordingly, when a task is performed on a specific stimulus, a memory trace of the stimulus, task and response is created. As a result, when a new task must be performed on the same stimulus in future trials, the memory trace of the now irrelevant task is recalled and must be suppressed in order to allow for a correct response to the current task, which slows down response time.

Results showed that both negative and competitor priming affected switch costs depending on the experimental context (Waszak et al., 2005). Specifically, it was determined that competitor priming effects occurred in all situations, suggesting that it is a combination of stimulus, task and response that are bound together in memory and consequently produce switch costs on later trials (Waszak et al., 2005); however negative priming was not without impact. Results showed that when the stimulus-set was small, participants were more likely to suppress the irrelevant task, producing switch costs on subsequent switch trials. Further investigations found that this task-suppression resulted from the increased activation of stimulus codes, suggesting that distractor suppression was only required when the stimulus codes of the to-be-ignored task were highly activated; an idea that follows along with the dominance hypothesis set out by the Task-Set Inertia model (Allport et al., 1994).

While these S-R association models provide a reasonable explanation as to the sources of task-switching costs, there are several instances in which these accounts come up short. For instance, in many of the previous investigations, switch costs have been found when the models would have predicted their absence. In fact, Allport et al. (1994) found that when participants were asked to switch between neutral Colour-naming task (coloured x's) and the neutral Word-naming task (words printed in black ink), switch costs were found. Given the task-specific nature of the stimuli, this result contradicts the ideas put forth by the S-R association models that switch costs should only be produced by the interference when stimulus overlap occurs between the two tasks.

Further contradictions have been found in regards to the sustainability of the S-R associations over several trials. As outlined in the above studies, response costs have been shown to effect several trials after a switch trial, increasing RTs of both task-switch and task repetition trials (Allport et al., 1994; Allport & Wylie, 1999; Wylie & Allport, 2000). Furthermore, this S-R priming can reoccur even after a lag of several hundred trials (Waszak et al., 2003, 2005); however, many researchers have found that switch costs are restricted to the immediate switch trial only, with no further costs occurring on the subsequent trials (Gopher, Armony & Greenshpan, 2000; Rogers & Monsell, 1995). These findings suggest that the inertial quality of S-R associations is not consistent and thus, when taken together with the idea that stimulus-task overlap is also not necessary for switch costs, it may be that other mechanisms are involved in the production of task-switch behavior.

Executive Control Models of Task-Switching

The weaknesses listed above have led many researchers to question the accuracy of the S-R association models of task-switching (e.g., Meiran, 2000; Rogers & Monsell, 1995; Rubinstein, et al., 2001). In particular, researchers have proposed a number of stage-like models, which outline a significant role for executive control in the production of switch costs. In its most common conceptualization, executive control is considered to be a conscious and flexible top-down processing component that allows for the selective activation and inhibition of specific S-R associations. According to the executive control models of task-switching, this top-down processing occurs in two distinct components that allows for successful task-set reconfiguration.

The first component is believed to occur prior to stimulus presentation, assuming that participants are given an appropriate preparation interval; however, if this interval is not provided, these initial processes will proceed after stimulus onset. It is hypothesized that this component is involved in initiating task-set reconfiguration, that is, it deletes the previous task-set, allowing the current task-set to be activated (Meiran, 2000; Rogers & Monsell, 1995; Rubinstein et al., 2001). It is also assumed that switch costs stemming from this portion of task-set reconfiguration can be reduced or even eliminated with a long cue-stimulus interval (approx. 500 ms or longer – Rogers & Monsell, 1995).

The second component also requires input from executive control processes; however, these processes can only be activated after the presentation of a stimulus. It is hypothesized that this component is responsible for overcoming the competing stimulus-cued activations from the previous trial and triggering the appropriate S-R associations for the current task (Meiran, 2000; Rogers & Monsell, 1995, Rubinstein et al., 2001). Researchers propose that the time course for completing this portion of the task-set reconfiguration is indicated by the large residual switch costs, similar to those reported by Allport and others (Allport et al., 1994, Allport & Wylie, 1999, Wylie & Allport, 2000). It should be noted that, while each of the executive control models support the idea of two distinct components, different terminology is often used. I will now review several of these models and the ways in which they explain the costs associated with task-switching behaviour.

The earliest model was outlined by Rogers and Monsell (1995). According to their *two-component model*, in order to execute a task correctly, an individual must adopt the appropriate task-set. This task-set includes representations of any potential stimuli, the task appropriate associations between these stimuli and the correct responses, and the relevant response codes to elicit the correct motor responses. Thus, switching from one task to another, requires an individual to abandon the previous, now irrelevant task-set and load the new, relevant task-set. In other words, successful task switching requires successful task-set reconfiguration.

As suggested by the name, the two-component model was hypothesized to involve two distinct control mechanisms. First, early task-set reconfiguration was thought to take place endogenously, that is, participants consciously switch to the appropriate task-sets; a switch that could occur without the presentation of a target stimulus (Rogers & Monsell, 1995). It was theorized that this endogenously-cued reconfiguration process would reduce switch costs by allowing the participants to enter a state of 'task-readiness' prior to the presentation of the stimulus. In order to measure the impact of this endogenous task-set reconfiguration, Rogers and Monsell manipulated the response-stimulus interval. Any changes in switch costs were hypothesized to represent the extent to which participants were able to endogenously reconfigure the task-set prior to stimulus presentation. Results indicated that following a short response-stimulus interval (i.e., 150 ms), switch costs were significantly larger compared to instances with a long response-stimulus interval (i.e., 1200 ms), suggesting that participants were indeed able to reconfigure task-sets prior to the stimulus presentation.

Yet, Rogers and Monsell (1995) found that not all switch costs were completely removed even after participants were allowed 1200 ms to prepare. Indeed, this is not a new finding. As reported earlier, Allport and his colleagues found several instances of persistent switch costs (Allport et al., 1994; Allport & Wylie, 1999; Wylie & Allport, 2000), which they used as evidence for the stimulus-cued priming effect. While Rogers and Monsell (1995) agreed that the stimulus could cue irrelevant task information from the previous trial, they felt that it was not directly responsible for the switch costs. Instead they suggested that residual switch costs result from the time required for the exogenously-cued control processes to selectively inhibit the irrelevant information and complete the task-set reconfiguration for the relevant task. Furthermore, they suggested that this stimulus-cued competition was not necessary to produce switch costs, proposing that the time required to complete the task-set reconfiguration during unrelated task-switches would also produce task-switch costs.

By presenting a role for executive control within task-switching behaviour, Rogers and Monsell (1995) were able to provide explanations for the earlier discrepancies surrounding the S-R association models presented earlier. For instance, it seems reasonable that the switch costs found during the All-Neutral condition of Allport et al. (1994) were the result of a successful task-set reconfiguration carried out by exogenously-cued processes. Furthermore, the idea of task-set reconfiguration itself suggests that a correct response execution is indicative of a successful reconfiguration and thus switch costs should be limited to the immediate task-switch trial. While this hypothesis contradicts the findings of Allport and others (e.g., Allport et al., 1994), Rogers and Monsell (1995) were able to clearly illustrate that switch costs can be restricted to the first switch trial and do not persist into the subsequent task-repetition trials; a finding that questions the role of proactive interference and task-set inertia in producing switch costs.

The generalizability of S-R priming models has been further questioned by more recent studies that have also found evidence supporting an executive control model of task-switching. For instance, Meiran (2000) has proposed his own stage-like model of task-switching, which also presents two different roles for executive control processes. Accordingly, when a task-switch trial occurs, the participant's executive control system must first reconfigure the task-set by biasing the *stimulus-set* toward the appropriate task. That is, the executive control system must alter the mental representations of the stimulus in terms of the relevant task attributes. Again, this process occurs endogenously, allowing the presented stimulus to be correctly identified in terms of the appropriate task. For instance, if the participant was previously presented with the number

3 on a number magnitude task (i.e., less than or greater than 5) and must now respond to that stimulus on a number parity task (i.e., even or odd), their executive control system would bias their stimulus-set to change the mental representation of '3' from 'less than 5' to 'odd.' Not surprisingly, this process was also affected by preparation time, producing smaller switch costs during larger preparation intervals; a finding that further supports the role of endogenous executive control in task-switching behaviour (Meiran, 2000; Rogers & Monsell, 1995).

Meiran (2000) also suggested that executive control was responsible for selecting the correct response; however, he outlined two different types of exogenously-cued response-sets. The *previous response-set* refers to the activation bias of the previous response on the current trial (proactive interference), where as the *alternative response-set* refers to the activation bias of the current response. According to Meiran (2000), at the beginning of a trial the previous response-set holds a stronger bias than the alternative response-set; however, if we continue with the example presented above, once a participant has identified a stimulus, a stimulus-matching process begins, which activates the task-appropriate response representations (i.e., left button = odd, right button = even) and compares them to the established stimulus representation. In other words, the stimulus representation of 'odd' is compared to the response representations of both 'odd' and 'even.' This comparison biases the response-sets in the direction of the response that is most similar to the stimulus representation, which, in our example, is the response associated with 'odd.' Accordingly, this produces a stronger bias for the alternative response, which is, ideally, the correct task-appropriate response.

In terms of task-switching costs, it is this response-set reconfiguration that is hypothesized to increase response times following the response selection process, and consequently produce the residual switch costs seen throughout the literature (e.g., Allport et al., 1994; Rogers & Monsell, 1995; Wylie & Allport, 2000). Indeed, manipulations of task preparation did not affect the impact of response-set reconfiguration during experimental tests of the model. These findings also led researchers to suggest that the reconfiguration of response-sets cannot occur at the same time as the reconfiguration of stimulus-sets (Meiran, 2000); a reasonable hypothesis given that the executive control system is known to be limited in its processing resources.

Again, the findings of Meiran (2000), like Rogers and Monsell (1995) suggest that residual switch costs are not a definitive indicator of a passive stimulus-based retrieval of previous S-R associations, proposing instead that they reflect a task-set reconfiguration carried out by executive control processes. These ideas were followed by a similar model suggested by Rubinstein and colleagues (2001). According to their investigations, task-switching involves a endogenously-cued goal-shifting component followed by an exogenously-cued rule activation component. When a participant begins a switch trial, it is the responsibility of the goal-shifting stage to remove the task-goals of the previous trial from declarative working memory, replacing them with the appropriate task goals for the current trial. This change allows the presented stimulus to be interpreted correctly and associated with the appropriate response. As with other models, Rubinstein and colleagues (2001) hypothesized that goal-shifting can occur prior to stimulus presentation when sufficient task preparation is allowed; however, this hypothesis was not tested directly and can only be seen a speculative.

Once the correct task goal has been inserted into the individual's declarative memory and the correct stimulus attributes have been identified, Rubinstein et al. (2001) proposed that the rule activation stage is then implemented. As the name suggests, the stage activates the relevant task response rules while disabling the irrelevant task response rules. Evidence shows that this activation of new task rules depends on the familiarity and complexity of both the previous and current task rules. Specifically, switch costs were greater when participants were asked to switch from a familiar task to an unfamiliar task. Similarly, switch costs were also increased when the task rules increased in complexity. As mentioned above, Rubinstein et al. (2001) did not allow for any substantial task preparation prior to stimulus presentation. Consequently, no hypotheses were made regarding residual switch costs; however, speculations could be made to suggest that rule activation is the most likely source for residual switch costs.

Summary

Given that strong evidence has been provided for both types of models, it seems likely that task-switch costs stem from a combination of carryover effects from previous S-R associations and executive control processes. Indeed overlap between the different models are obvious. For instance, Waszak et al., (2003) allow for the possibility that executive control processes are needed for participants to accurately switch between tasks, although they argue that this is not the direct source of the switch costs; Conversely, Rogers and Monsell (1995) suggest that the stimulus presentation can activate the S-R associations from previous trials; however, they propose that this activation only increases time needed by the exogenous control processes to successfully complete the task-set reconfiguration. They state that the switch cost itself results from the executive control processes and occurs even in situations where there are no S-R overlaps. While this debate has yet to be resolved, the ideas brought forth by the different sides allow researchers to begin expanding the paradigm to investigate the impact of some more complex factors that may be involved during real-life task-switches.

The Present Study

One of the more complex factors that may impact task-switching behaviour is response complexity. In previous studies, a simple single index-finger response was primarily used to measure task-switch effects; however, this response does not allow the results to be expanded to more complex task situations. Moreover, real-world instances of task-switching, such as those found while driving, are likely to require several different response possibilities and these individual responses may include several different components that must be successfully reconfigured for a response to be executed. Currently, it has been shown that performing more than one task while driving can impede responses (e.g. Gugerty, Rakauskas & Brooks, 2004); however, no studies have directly investigated the effects of task-switching on driving behaviour. While it is not the immediate goal of the present study to apply the task-switching paradigm to a driving scenario, it is expected that by investigating the impact of increased response complexity on task-switching costs, the present study will help to expand the task-switching paradigm to a more real-world application.

Not surprisingly however, response complexity can manifest itself in many different ways. For the current study, response complexity was studied in two distinct ways. Firstly, we defined response complexity as an increase in the number of stimulus-response pairs. It has been demonstrated previously that an increase in the number of S-R pairs can significantly increase RT. For instance, in a study by Miller and Ulrich (1998), RTs increased when the number of S-R pairs also increased. This finding was further supported by their investigations of the *lateralized readiness potential (LRP)*, an event-related potential thought to indicate the beginning of the motor activation for the selected response hand. In particular, they found that the increase in S-R pairs resulted in a significant increase in time between the stimulus presentation and the LRP onset. Accordingly, the authors proposed that increases in S-R pairs lengthen the time course of pre-hand selection processes, thereby delaying the response selection and activation of the appropriate hand.

These findings lend themselves well to investigating response complexity within the task-switch literature, particularly within the models of executive control. As demonstrated by previous research, endogenous control processes can significantly increase RTs during switch-trials if the participants are not given a sufficient preparation interval. Furthermore, it has been suggested that these endogenously produced switch costs result from a shift in the task-set goals (Rogers & Monsell, 1995; Rubinstein et al., 2001). This shift is carried out by executive control processes that delete the previous and now irrelevant task-set and activate the current and relevant one. Based on these ideas of executive control models, it seems reasonable to predict that the number of S-R pairs would significantly impact the time course of the pre-stimulus endogenous processes by increasing the time needed to delete and load task-sets. This is the first hypothesis investigated by the current study.

Specifically, we manipulated the number of S-R pairs in a manner similar to that of Miller and Ulrich (1998). In their study, they increased the number of S-R pairs by increasing the number of responses required by each hand (e.g., from 1 response to 3 responses). We applied this method using two groups of participants who performed the task-switching paradigm in two different conditions. In the first condition, participants were asked to respond with single button *index* finger responses. In the second condition, participants were asked to respond using both a single button *index* finger response and a three button *index-ring-middle* finger response as indicated by the stimulus. The number of presented stimuli remained the same in both conditions (i.e., 8 digits), thus the increase in S-R pairs stemmed from the increase in the number of responses required by each hand. Results indicated an increase in switch costs as the number of

S-R pairs increased, suggesting that the time required to load a task-set increases when the number of S-R pairs within that task-set also increases.

Yet these results were confounded by the fact that the number of S-R pairs were increased by increasing the number of within-hand responses. This confound stems from the results presented by Miller and Ulrich (1998), in which they determined that both the number of S-R pairs and the number of within-hand responses affect response processes differently. Consequently, follow-up studies were required to isolate how the switch costs were being impacted by the increase in S-R pairs, or if it was instead an increase in the number of within-hand alternatives that produced the increased costs. The results of these studies are discussed in detail in later sections.

While the findings of the above studies provided us with some information about the effect of response complexity on switch costs, they were unable to address a different but equally important manifestation of response complexity, which impacts the *Response Repetition effect.* Originally demonstrated by Rogers and Monsell (1995), the response repetition effect can be found on both task-switch and task-repeat trials. For instance, during task-repeat trials, Rogers and Monsell (1995) found that RTs were smaller and error rates were lower when the participants were asked to repeat the same response from the previous trial compared to when they were asked to switch their response. This finding falls in line with previous studies that have consistently illustrated a decrease in RT when the repetition of a response signal occurs for two or more consecutive trials (e.g., Bertelson, 1963). Initially, it was expected that this benefit would carry over on switch trials, decreasing the switch costs (Rogers & Monsell, 1995); however, subsequent investigations have produced a different pattern of results.

In particular, during switch trials, costs in both RT and errors were found to be even larger when participants were asked to repeat the same response, compared to instances in which they were required to switch between different responses (e.g., Hubner & Druey, 2008; Rogers & Monsell, 1995). Although several suggestions have been made as to the source of these extra costs, recent research has provided strong evidence to suggest that these costs result from inhibition that occurs in the previous trials (Meiran, 2000; Steinhauser, Hubner & Druey, in press; Rogers & Monsell, 1995). In early models, (e.g., Meiran 2000), it was theorized that during a trial, the executed response gained a stronger association with the appropriate stimulus attribute. For instance, if participants were required to respond to an up-down task using the 'up-left' response key, the activation of the 'up' component of the response would become stronger than the 'left' component. Consequently, if participants were required to respond to a right-left task in the following trial, more resources would be needed to bias the response system toward the correct 'left' response, increasing RT and producing more errors.

This finding recently gained more support with a study conducted by Steinhauser and colleagues (in press). They utilized the LRP to investigate response inhibition and its effect on task-switch/response repetition trials. They found that during the cue-stimulus interval of a trial, the LRP tracked toward the polarity opposite to the previous trial. This drift biased participants to respond correctly when they were required to switch responses but biased them incorrectly when the response repeated. Furthermore, it provides evidence consistent with the idea that a response is inhibited following its execution during the previous trial. It is this inhibition that plays a key role in our second hypothesis of response complexity.

In particular, we suggested that response complexity could also be defined as an increase in the number of components within an individual response. Indeed, research has found that RT is increased as the number of individual response elements are also increased (Sternberg, Monsell, Knoll, & Wright, 1978). Thus, it was hypothesized that when participants were required to increase the number of response components from a single *index* finger response to a three button *index-ring-middle* finger response, increased response repetition effects would be found. Furthermore, we suggested that these findings would indicate the increased time required to overcome the additional inhibition produced by the extra response components. To test this hypothesis, we included a third condition in Experiment 1. In this condition, participants were required to perform the task-switch paradigm using only three button *index-ring-middle* finger responses. Results indicated a trend that this increase in the number of response components may indeedincrease the response repetition effect. The implications of these findings are discussed in later sections.

In summary, the goal of the present study was to investigate the role of response complexity in two different ways. We hypothesized that increases in response complexity would not only increase task-switch costs but also the additional response repetition costs. We designed Experiment 1 to establish the possible roles played by response complexity during task-switching. We then performed a series of follow-up studies in an attempt to tease apart the different components of response complexity and investigate their unique impact on task-switch costs.

Experiment 1

The goal of Experiment 1 was to establish the effect of response complexity. Participants were asked to perform two different tasks: a parity task (i.e. is the number *even* or *odd*), and a magnitude task (i.e. is the number *less than* or *greater than* 5). Each participant was randomly assigned to one of three conditions. In the Single-Button condition, participants were required to perform the task-switching paradigm using single-button *index* finger responses (see Figure 1a). In the Three-Button condition, participants were required to respond with three-button *index-ring-middle* finger responses (see Figure 1b). Both the Single-Button condition and Three-Button condition contained 16 S-R pairs; however, the Both Button Condition required participants to perform both single-button *index* finger responses and three-button *index-ring-middle* finger responses as cued by the stimulus, creating 32 S-R pairs (see Figure 1c).

We used these three conditions to test two different hypotheses. First, RTs between the Single-Button condition and the Both Button Condition were compared to determine if increasing response complexity by increasing the number of S-R pairs impacted the switch costs. We hypothesized that switch costs would increase with increased response complexity due to the time required to delete and activate the appropriate S-R pairs. We also investigated response complexity by increasing the number of response components between the Single-Button condition and Three-Button condition (e.g. 1 or 3 finger responses, respectively). It was hypothesized that this increase in response complexity would increase the response repetition effect on task-switching costs.

Method

Participants. Data was collected from 65 individuals (20 per condition, 5 were removed) from the Wilfrid Laurier University undergraduate and graduate populations. The mean age was 20.2 years. When appropriate, compensation was given in the form of course credit.

Materials. A series of target numbers from one through nine (excluding five) were presented on a black background in a pseudorandom order. Numbers were 10 mm high and 8 mm wide. Red numbers instructed participants to perform the parity task whereas green numbers instructed participants to perform the magnitude task. When necessary (e.g., the Both Button

Condition), numbers were displayed within a white circle or square to indicate the appropriate finger response. All experimental programs were created in DirectRT (Empirisoft, New York, NY) and participants gave responses via an Empirisoft button box (New York, NY). To control for any effects due to handedness, or red-green colour blindness, a demographics questionnaire and the Dutch Handedness Questionnaire were administered at the beginning of each study. Only right-handed participants with normal colour vision were used. For informational purposes, age and gender data were also collected.

Procedure. Participants were seated in front of a PC computer in an isolated booth. The consent form was signed and participants completed the demographics and handedness questionnaire prior to the experiment. Instructions were presented visually on the screen and explained verbally to the participant. Based on the findings of previous pilot studies, the experiment began with eight blocks of 50 practice trials. To ensure participants received equal practice on each type of trial combination (e.g. task-switch, task-repeat, response-switch, response-repeat), an equal number (i.e., 100) of the condition appropriate trials were pseudorandomly presented.

Each trial began with the presentation of a coloured number stimulus that indicated the appropriate judgment task to be performed (see Figure 1a-c). In order to increase the endogenous switch costs, no preparation interval was given. For the even/odd task, even number responses were made with the left hand and odd number responses were made with the right hand for 50% of the participants. The other 50% of participants made responses with the opposite hands. Similarly 50% of participants responded with their left hand for numbers less then 5 and responded with their right hand for numbers greater than five. Again, the other 50% produced responses with the opposite hands. Responses for the two tasks were randomly counterbalanced across participants.

Participants were asked to respond as quickly and as accurately as possible with the appropriate number of button presses. Each trial continued automatically following a response. After each block of practice trials, participants were given the option of having a short break. A break was also allowed following the completion of all practice trials.

The experimental session was also divided into eight blocks of 50 trials; however, an additional block of 100 practice trials were added at the beginning of the session to allow participants to refamiliarize themselves with the tasks and responses following the break. The trial structure and responses outlined above were repeated in the experimental blocks. Again, an equal number of condition-appropriate trials were pseudorandomly presented to the participant. Small, optional breaks were given between each block of trials. Again, participants were reminded to respond as quickly and as accurately as possible, and responses were recorded by the computer for later analyses.

Results

As outlined in past literature, data were removed from analyses if the RTs were less than 50 ms or greater than 3000 ms. Incorrect responses as well as any trials immediately following incorrect responses were also removed. This criteria resulted in approximately 1% of trials being removed in the Single-Button Condition, 3% of trials being removed in the Three-Button Condition, and 4% of trials being removed in the Both Button condition. Average RTs for correct responses and the total number of removed trials were calculated and used in the following analyses. Participants were removed from the data if they had more than 25% of their trials removed. This criterion led to five participants being removed and replaced in the Both Button condition.

Increase in the Number of S-R Pairs

A two-way ANOVA was calculated for both RTs and errors with Task (switch or repeat) and Condition (Single Button or Both Button) as independent variables. In our analysis of RT, we found a main effect for Task, which indicated that participants were slower to respond on Task-Switch trials compared to Task-Repeat trials, $F(1, 38) = 142.92, p < 0.001$ (see Figure 2). Further analyses also revealed a main effect of Condition with participants responding faster in the Single Button condition than in the Three-Button condition, $F(1, 38) = 24.50, p < 0.001$ (see Figure 3). The interaction between these factors was also found to be significant. In particular, we calculated switch costs for both conditions by subtracting RTs during task-repeat trials from RTs during task-switch trials and found that switch costs increased during the Both Button condition compared to the Single Button condition, $F(1, 38) = 4.22, p = 0.047$ (see Figure 4).

Error analyses indicated a significant main effect of Condition. Participants produced more errors during the Both Button condition than during the Single Button condition, $F(1, 38) = 35.49, p < 0.001$ (see Figure 5). Results also suggested a trend that participants produced more errors during Task-Switch trials ($M = 23.15$) compared to Task-Repeat trials ($M = 20.73$); however, this result did not reach significance, $F(1,38) = 3.40, p = 0.073$. This trend was further supported by the interaction trend, which suggested that switch costs were again larger during the Both Button condition ($M = 4.5$) than during the Single Button condition ($M = 0.35$), $F(1,38) = 2.49, p = 0.1228$.

Increase in the Number of Response Components

A three-way ANOVA was conducted for both RTs and Errors with Task (switch or repeat), Response (repeat or switch) and Condition (Single Button or Three Button) as independent variables. Results indicated a main effect of Task, indicating participants were faster to respond during task-repeat trials compared to responses during task-switch trials, $F(1,38) = 122.33, p < 0.001$ (see Figure 6). No other main effects were significant; however, Task and Response did produce a significant interaction, indicating a response repetition effect, $F(1,38) = 62.12, p < 0.001$ (see Figure 7). Specifically, during task-repeat trials, participants were faster when they were required to repeat the same response compared to when they were required to switch responses $F(1, 38) = 50.20, p < 0.001$; however, during task-switch trials, participants were faster when they were required to switch responses than when they were required to repeat the same response, $F(1, 38) = 16.76, p < 0.001$. No other significant interactions were found. Nevertheless, a trend toward a three-way interaction was found, suggesting that the response repetition effect may be larger in the Three Button condition compared to the Single Button condition, $F(1,38) = 2.20, p = 0.1465$ (see Figure 8a-b).

Our error analyses also revealed a significant main effect of Task, indicating that participants made more errors during task-switch trials compared to task-repeat trials, $F(1,38) = 5.42, p = 0.025$ (see Figure 9). The main effect of Condition was also significant, with participants producing more errors when asked to make a single button press compared to when responses required three button presses, $F(1, 38) = 6.80, p = 0.0129$ (see Figure 10). Two significant interactions were also found. Firstly, a significant two-way interaction was found between Task and Response, again indicating a response repetition effect, $F(1, 38) = 15.11, p < 0.001$ (see Figure 11). Specifically, during task-repeat trials, participants tended to make more errors when asked to switch responses than when they were asked to repeat the same responses,

$F(1, 38) = 12.34, p = 0.001$. Conversely, during task-switch trials, the relationship was reversed with participants producing more errors during response repeat trials compared to response-switch trials, $F(1, 38) = 6.43, p = 0.015$.

The three-way interaction revealed, however, that the response repetition effect stemmed mainly from the three-button condition, $F(1, 38) = 8.22, p = 0.007$. As illustrated in Figure 12a, the response repetition effect was not found when participants were asked to respond with just a single button press, $F(1, 19) = 1.07, p = 0.314$; however, when participants were required to use a three-button response, the number of errors increased during switch trials when they were asked to repeat the previous response, $F(1, 19) = 15.06, p = 0.001$ (see Figure 12b).

Discussion

The purpose of Experiment 1 was to determine the effect of response complexity on the costs incurred when participants switch between two different tasks. We defined response complexity in two distinct ways. Firstly, we suggested that response complexity referred to the number of S-R pairs required for each task. Previous research has established that the number of S-R pairs can significantly increase the pre-hand selection processes that occur following the presentation of the stimulus (Miller & Ulrich, 1998). It is thought that, although the stimulus is used as a task-cue, these processes occur endogenously and must be completed before the stimulus can be successfully identified according to the task-appropriate attribute (Rogers & Monsell, 1995; Rubinstein et al., 2001).

Accordingly, we hypothesized that increases in the number of S-R pairs would increase the time required to complete the endogenous processes. Moreover, we believed that this increase in endogenous processing time would stem from the increase in the time required to activate and delete more S-R pairs into and out of working memory. Our data not only replicated the findings of previous research but also supported our hypothesis. Firstly, we found a significant task-switch effect in both RTs and error rates with participants requiring more time to switch between two different tasks than they required to repeat the same task. These findings are not surprising but do provide further support for the similar findings found in the previous research (e.g Allport et al., 1994; Rogers & Monsell, 1995).

Participants were also slower to respond in general as the number of S-R pairs increased. This finding replicates the previous studies of Miller and Ulrich (1998) as well as others (e.g., Brainard, Irby, Fits & Alluisi, 1962), which state that an increase in the number of S-R pairs increases RT. Furthermore, we have provided additional evidence that the number of S-R pairs increases the pre-hand selection processes as suggested by these other researchers. Specifically, we found that when participants were required to delete and activate more S-R pairs in their working memory, they subsequently required more time to switch between different tasks. Although these findings were not replicated in terms of error rates, a trend was found, suggesting that participants were also more likely to make errors as the loading time increased.

Not only do these findings support our hypothesis, they allow us to extend the previous literature. As stated above, endogenous control processes are used to delete the now irrelevant S-R pairs from the previous task and activate the relevant S-R pairs for the current task, which allows participants to accurately identify the stimulus in terms of the task-appropriate attribute (Rubinstein et al., 2001; Rogers & Monsell, 1995). Thus, the results suggest that by increasing response complexity in terms of the S-R pairs, participants require more time to delete the previous S-R pairs and load the new ones during switch trials. Consequently, the endogenous processing time is increased, which lengthens the time needed to identify the stimulus and produces larger switch costs.

Overall, in regards to our first hypothesis, the findings suggest that task-switching is impacted by an increase in response complexity, with switch costs increasing following an increase in response complexity; however, we also found the increased response complexity slowed RTs overall in both the task-repeat and task-switch condition. In regards to the task-repeat condition, this result is slightly surprising. According to our original hypothesis, we expected an increase in response time when participants were required to delete and activate more S-R pairs. This increase would be evident with increased switch costs; an idea that is supported by our results. Conversely, we expected that if no changes were needed to the previous S-R pairs during the current trial, as in a task-repeat trial, there would be no increase in the subsequent RT. Our results indicate that this was not the case; however, we suspect that the increase in RT found during task-repeat trials stems from the increased time of the post-response selection processes, which occurs with more within-hand alternatives (i.e. 1 vs 2 alternatives). We tested this possibility in Experiment 3.

Although our results do provide strong evidence that increasing response complexity in terms of S-R pairs increases switch costs, the results are confounded by the fact that we increased the number of S-R pairs by increasing the number of within-hand alternatives. According to previous research, the number of S-R pairs and the number of within-hand alternatives can independently impact RTs (Miller & Ulrich, 1998). Specifically, the number of S-R pairs has been found to increase the pre-hand selection responses, at least in regards to hand selection. Conversely, an increase in the number of within hand-alternatives has been found to increase the time required for post-hand selection processes (e.g., finger selection and response programming). Furthermore, switching between one and three finger responses did appear to increase the overall difficulty of the task, which most likely led to the increase in task-repeat RT in Condition 3. We conducted two follow-up studies to address these issues. In Experiment 2, we manipulated the number of S-R pairs while keeping the number of within-hand alternatives consistent. We then performed Experiment 3 in which we manipulated the number of within-hand alternatives, while keeping the number of S-R pairs consistent.

We also investigated another conceptualization for response complexity. We suggested that response complexity may also manifest itself in terms of the number of response components included within an individual response; however, we hypothesized that this type of response complexity would not directly impact the switch costs themselves but instead increase the response repetition effects found between task-repeat and task-switch trials. As mentioned above, task-repeat trials are unaffected or even benefit when a participant repeats the same response from the previous trial; however, on switch trials, this response repetition is detrimental, increasing the usual costs found during task-switches. (e.g., Rogers & Monsell, 1995). It has been suggested that this increase stems from the suppression of the previously executed response on the current trial (Meiran, 2000; Steinhauser et al., 2009). Thus, if we increase the number of components to be suppressed then we should increase the response repetition costs during switch trials when participants are required to overcome the suppression and repeat the same response.

According to our results, this hypothesis is at least partially supported. Firstly, the Response Repetition effect was replicated for both RT and error rates. In other words, response repetitions produced benefits during task-repeat trials but produced increased costs during switch trials; however, at least in terms of error rates, this effect occurred only when participants responded with the more complex three-button response. The finding that single-button responses did not produce a response repetition effect in error rates is not uncommon. Many studies have found that the response repetition effect to be limited to RTs (Meiran, 2000; Rogers & Monsell, 1995); however, the lack of significant effect for the error rates is likely due to the simplicity of single button presses, which allows participants to produce accurate response even when the response is repeated. The increased response complexity may have increased the difficulty enough to produce the response repetition effect shown in Figure 12b. Unfortunately, we were unable to produce a similar effect with RTs. Nevertheless, we found a trend to suggest that increased response complexity may also be slowing the time required to switch trials when a response needed to be repeated. Future investigations will be needed to determine if response complexity does indeed increase the response repetition effect in terms of response time or if this effect is limited to error rates.

Taken together, these findings provide additional evidence that the response repetition effect is indeed the result of response suppression. Furthermore, we found that the more components in a response, the more that response is suppressed following execution. It is then more difficult to activate this response if it is required on the subsequent trial. In other words, we suggest that when participants are producing either a single or a three component response, they suppress all required components following response execution; however, when they must produce the same response on the following trial, it requires more time to activate the three suppressed components compared to the single suppressed component. Consequently, response repetition costs found during switch trials are increased.

Experiment 2 and 3

Given that the results of increased S-R pairs in Experiment 1 could have been confounded by the increase in the number of within-hand alternatives, we designed Experiment 2 and 3 to isolate the effects of both factors. In Experiment 2, we manipulated the number of S-R pairs while maintaining a constant number of within-hand alternatives. We hypothesized that if increasing the number of S-R pairs did indeed increase switch costs as suggested by Experiment 1, then we should see a significant difference when we increased the number of S-R pairs from 16 to 32. Conversely, in Experiment 3 we manipulated the number of within-hand alternatives while holding the number of S-R pairs constant. In this experiment, we hypothesized that there should be no differences in the switch costs produced when the number of within-hand alternatives is increased; however, the increased difficulty created by the multiple within-hand responses should produce an overall slowing of RT.

Method: Experiment 2

Participants. Data were collected from 41 individuals (20 per condition, 1 was removed) from the Wilfrid Laurier University undergraduate and graduate populations. The mean age of all participants was 18.5 years. When appropriate, compensation was given in the form of course credit.

Materials. All materials were the same as those outlined in Experiment 1 with a few changes. First, the numbers 6-14 were presented in the 16 Pairs condition and the numbers 2-18 were presented in the 32 Pairs condition. This large range allowed for an adequate manipulation of the number of S-R pairs (i.e., an increase from 16 S-R pairs to 32 S-R pairs). The change in stimuli also required a change in the magnitude task. Specifically, participants were now asked to determine if the stimulus was less than or greater than 10, following the presentation of a green number. Red numbers still required that a parity judgment be made. Furthermore, participants only needed to produce single button index finger responses and thus, white circles and squares were no longer presented with the target number as in the Both Button condition of the Experiment 1.

Procedure. Participants experienced a similar procedure as that outlined for Experiment 1 (see Figure 13); however, given the simplicity of the responses required for Experiment 2, participants were only required to complete four blocks of 50 practice trials as opposed to the eight blocks required in Experiment 1.

Results

Again, data were removed from the analyses if RTs were less than 50ms or greater than 3000ms. Incorrect responses and any trials immediately following incorrect responses were also removed. Based on these criteria, approximately 7% of the trials were removed from the RT analyses in the 16 Pairs condition and approximately 4% of trials being removed from RT analyses in the 32 Pairs condition. Participants with more than 25% rejected data were removed and replaced. This resulted in only one participant being excluded in the 32 Pairs condition. No other participants were removed. Average RTs for correct responses and the total number of removed trials were calculated and used in the following analyses.

A two-way ANOVA was conducted with Task (switch or repeat) and Condition (16 S-R pairs or 32 S-R pairs) as the independent variables. This analysis indicated a significant main effect of Task. Specifically, RTs were shorter during task-repeat trials than during task-switch trials, $F\,(1,38) = 151.90, p < 0.001$ (Figure 14a). There was no significant main effect of condition nor was there a significant interaction effect. The error analysis revealed similar findings, with a significant main effect of Task indicating that participants made less errors during task-repeat trials than during task-switch trials, $F\,(1,38) = 13.08, p = 0.009$ (Figure 14b). Again no other significant effects were found.

Method: Experiment 3

Participants. Data were collected from 45 participants (20 per condition, 5 were removed) sampled from the undergraduate and graduate populations of Wilfrid Laurier University. The mean age of all participants was 20.25 years. Again, when appropriate, compensation was given in the form of course credit.

Materials. To manipulate the number of within-hand responses without manipulating the number of S-R pairs, we replaced our number stimuli with a series of red and green target letters. This change removed the participants' ability to categorize the stimuli (e.g. even/odd, less than/greater than), which would increase the number of S-R pairs when then number of within-hand responses was also increased.

The letters were displayed on a black background and presented in a pseudorandom order. In the 1-Alternative condition, the letters B, W, L, S, F, Q, M and H were used as target letters, whereas in the 2-Alternative condition, the letters B, W, F and Q were presented. Target letters were 10 mm high and 8 mm wide and were displayed above or below a white line, which indicated the appropriate task. For both conditions, the target letters were presented within a white circle or square. As with Experiment 1 and 2, all experimental programs were created and run using DirectRT (Empirisoft, New York, NY) and all responses were given via an Empirisoft button box (New York, NY). Demographic and handedness information was also collected.

Procedure. As with Experiment 1 and 2, participants were asked to sign a consent form and complete the demographics and handedness questionnaires prior the beginning the computer tasks. Again, participants completed eight blocks of 50 practice trials, with each block being followed by a short break. A longer break was also allowed following the completion of all practice blocks. Each trial type was presented equally and in a pseudorandom order; however, some response repetition trials (e.g., single button index finger responses required on two consequent trials) were included to ensure that switches between the single button and three-button response types appeared as random as possible within the blocks.

The first trial began with the presentation of a white line that remained on the screen for the entire block. Participants were then presented with a letter displayed within a white square or circle. In the 2-Alternative condition, a white square indicated that a single button *index* finger response was required whereas a white circle indicated that a three button *index-ring-middle* finger response was required (see Figure 15a). When the letter and shape appeared above the line, participants were required to determine the colour of the letter. Conversely, when the letter and shape were presented below the line, the participants were required to respond to the name of the letter. Responses were to be made as quickly and as accurately as possible. Also, to ensure that both conditions were equal in perceptual difficulty, participants in the 1-Alternative condition were presented with white squares (see Figure 15b); however, no specific instructions were given.

The experimental blocks were very similar to the practice blocks; however, 12 blocks of 50 trials were presented. This increase was to allow for the presentation of 400 experimental trials and 200 response repetition trials, which ensured a pseudorandom presentation of the experimental trials. Again, participants were allowed short breaks between each block. Responses were recorded by the computer for later analysis.

Results

The same rejection criteria were used as in the previous studies. Based on these criteria, approximately 7% of the trials were removed from the RT analyses in the 1-Alternative condition and 11% were removed in the 2-Alternative condition. Five participants were removed and replaced due to error rates higher than 25%. Average RTs for correct responses and the total number of removed trials were calculated and used in the following analyses.

Again a two-way ANOVA was used for both RTs and error rates with Task (switch or repeat) and condition (1 or 2 within-hand alternatives) as the independent variables. A significant main effect was found for both task and condition. In particular, our results indicated that participants were slower during task-switch trials compared to task-repeat trials, $F(1.38) = 140.95, p < 0.001$ (Figure 16a). Similarly, participants were slower when the number of within-hand alternatives increased from one to two, $F(1, 38) = 7.85, p = 0.008$ (Figure 17a). There was no significant interaction between condition and task.

Similar results were also found in our error analyses. Specifically, participants made more errors when asked to switch to a different task than when they were asked to repeat the same task, $F(1, 38) = 11.18, p = 0.002$ (Figure 16b). We also found that participants were more likely to make errors when they were given two within-hand alternatives, compared to when they were given only one within-hand alternative, $F(1, 38) = 19.15, p < 0.001$ (Figure 17b). Again, no significant interaction was found.

Discussion

The goal of Experiments 2 and 3 was to further investigate task-switch costs by separating the effect of increasing the number of S-R pairs from the effect of increasing the number of within-hand alternatives. Previous research has suggested that these two factors do impact response processes differently and additively (Miller & Ulrich, 1998); however, our first study was unable to tease these effects apart. Consequently, we developed two hypotheses that were tested in the above studies. Firstly, we hypothesized that when we increased the number of S-R pairs from 16 to 32 without increasing the number if within-hand alternatives, the switch costs would significantly increase. Secondly, we expected that the number of within-hand alternatives would increase the overall RTs but would not have a direct impact on the switch costs.

Results only partially supported our hypotheses. Specifically, while we did find an overall increase in RT following an increase in number of within-hand alternatives, we did not find an increase in switch costs following an increase in the number of S-R pairs. These latter results are surprising, given that previous literature would suggest an increase in endogenous processing time with more S-R pairs (e.g., Miller & Ulrich, 1998; Rogers & Monsell, 1995); however, our non-significant findings may be due to a methodological difference in how we increased the number of S-R pairs in Experiment 2 compared to that of the previous research. In particular, Miller and Ulrich (1998) increased the number of distinct S-R pairs with each stimulus being mapped to only one response. We created a similar situation in Experiment 1, by manipulating the number of S-R pairs using two distinct responses in the Both Button condition, which produced significant findings; however, in our second study, we had participants map several stimuli to the same response and it is this difference that may have been a reason for our lack of significant effects.

Unfortunately, addressing this discrepancy may prove difficult for future researchers. The nature of the task-switching paradigm makes it challenging to pair individual stimuli with individual responses. Specifically, if participants were required to make distinct responses to each stimulus, the paradigm is transformed from an investigation of task-switching to one of choice response time. Careful consideration and some creativity needs to be taken by researchers to overcome this problem; however, it is hoped the future investigations will be able to address this issue and thoroughly evaluate the relationship between increasing S-R pairs (response complexity) and task-switching behaviours.

Another possible explanation is that we did not actually increase the number of S-R pairs. Instead, participants may have categorized stimuli not by their number (e.g. 2) but by their task-category (e.g., even). If the stimuli were categorized by even/odd or less than/greater than 5 (or other possible categories such as "left/right hand"), then our manipulation of S-R pairs was not a manipulation at all. Instead each condition had four S-R pairs (i.e., left index = even/less than 5, right index = odd/greater than 5), no matter how many numbers were presented. If participants did indeed categorize the stimuli in this manner, then it would explain why we found significant results in Experiment 1, in which participants had four S-R pairs in the Single Button condition but eight S-R pairs in Both Button condition, but not in Experiment 2. Again, resolving this issue may prove challenging for future studies.

One possible solution is to increase the number of task-categories. For instance, participants could perform a colour-naming task with blue, red and green as the response categories; however, there are very few tasks that lend themselves to using three task categories. Furthermore, for the three task categories to be used as a successful manipulation of S-R pairs, there must also be three distinct responses that do not increase the number of within-hand alternatives. Given that participants only have two hands, this criterion is difficult to meet; however, it may be possible to utilize vocal responses or motor responses that allow for more options (e.g., joystick movement) to accommodate the increase in the number of task categories.

To return now to our second hypothesis, the present results support the idea that more within-hand alternatives increases the overall response time and explain the increased RT found during task-repeat trials in Experiment 1. We would also like to emphasize that no interaction effect was found, indicating that the number of within-hand alternatives did not impact the size of the switch costs. Such findings further our notion that within-hand responses only influence that overall RTs and not the switch costs themselves. These results are also not surprising considering the findings of both Miller and Ulrich (1998) as well as more recent work by Hsieh and Liu (2005). Specifically, within-hand alternatives have been found to affect only the post-hand activation processes (Miller & Ulrich, 1998), while the task-switch costs most likely affect the pre-hand activation processes (Hsieh & Liu, 2005). Consequently, when participants were required to choose between two different response finger options, the increase in processing time would be additive to the switch costs. This delay would also impact task-repeat trials in a similar manner, resulting in the overall increase in RTs we found in both Experiment 1 and 3. It may, however, be worthwhile to manipulate the processes associated with the task switch itself (e.g. from hand to finger) to determine if increases in within-hand response alternatives can impact switch costs under specific circumstances.

General Discussion

The goal of the present studies was to address an important issue within the task-switching literature. According to previous studies, task-switching costs stem from both endogenous and exogenous processing (Allport et al., 1994; Rogers & Monsell, 1995; Rubinstein et al., 2001). They suggest that endogenous costs result from the extra time required to reconfigure the necessary task-set by deleting the previously relevant task-set and activating the currently relevant task-set (Rogers & Monsell, 1995; Rubinstein et al., 2001). This task-set reconfiguration allows for the stimulus to be identified according to the appropriate task attribute. Moreover, this cost occurs only when the participant is unable to prepare for a task-switch in advance. On the other hand, the stimulus-cued exogenous costs represent the time needed to overcome any previous S-R associations from recent trials and activate the correct S-R associations for the present trial; however it is debated as to whether this process occurs passively or with help from executive control (e.g., Allport et al., 1994; Rogers & Monsell, 1995). Unfortunately, these investigations have primarily involved single button *index* finger responses, making their application to more complex real-world responses difficult. Thus, we sought to investigate the impact of increased response complexity on task-switching costs, in hopes of bridging this gap.

The previous literature lends itself to two different definitions of response complexity. Firstly, we defined response complexity as an increase in the number of S-R pairs. In an investigation by Miller and Ulrich (1998), the LRP was used to study increasing numbers of S-R pairs. According to their results, higher numbers of S-R pairs increased the time required for pre-response selection processes, particularly in terms of hand selection. By using this localization of S-R pair effects as our foundation, we hypothesized that by increasing the number of S-R pairs we would increase the costs incurred during the endogenous pre-response selection stages of processing. In other words, we predicted that more time would be required to endogenously delete and activate the appropriate task-sets as the number of S-R pairs within the task-set increased. Moreover, we expected that this increase in RT would only occur during task-switch trials, given that task-repeat trials would not require any task-sets to be deleted or activated, thus the size of the task-set would not matter during these trials.

To test this hypothesis, we adapted the method of Miller and Ulrich (1998) in two different ways. In Experiment 1, we manipulated the number of S-R pairs by increasing the number of within-hand responses; however, as demonstrated by Miller and Ulrich (1998), the number of within-hand responses can increase RT independently of the number of S-R pairs.

Thus, to overcome this confound, we conducted Experiment 2 in which we increased the number of presented stimuli (e.g., 8 vs. 16). This manipulation allowed us to change the number of S-R pairs (16 vs. 32) while holding constant the number of within-hand alternatives. In a third experiment, we also tested the effect of within-hand alternatives separately from the number of S-R pairs. Our results supported the findings of Miller and Ulrich (1998), suggesting that within-hand alternatives do independently affect RT; however, as expected, no direct effects on switch costs were found.

More importantly, although we found some support for our hypotheses in Experiment 1, they were not substantiated in Experiment 2, suggesting that response complexity may not affect task-switching costs; however, it may be that our manipulation of the number of S-R pairs in Experiment 2 was insufficient to reproduce the effects found in Experiment 1. For instance, in Miller and Ulrich (1998), they manipulated *individual* S-R pairs with each stimulus being associated with only one response; however, in our second experiment, we manipulated the number of stimuli, but each stimulus was only associated with one of two different responses. Thus, while we increased the number of stimuli presented to the participants, we may not have adequately increased the number of S-R pairs.

The idea that the number of S-R pairs was inadequately increased in Experiment 2 is further supported by the significant findings of Experiment 1, in which the increase in within-hand alternatives allowed for an increase in the number of individual S-R pairs. Thus, a more appropriate interpretation of our results is that response complexity does impact task-switching behaviour, at least under certain circumstances; that is, increasing the number of *individual* S-R pairs does lengthen the endogenous processing time, which allows for the successful identification of the task appropriate stimulus attribute. It is hoped that future research will be able to successfully resolve this issue and provide an appropriate experimental manipulation to investigate switch costs during instances of increased response complexity; however, the limitations of the task-switching paradigm may prove to be a challenging obstacle to overcome.

In addition to our investigations of S-R pairs, we also investigated a second definition of response complexity. In previous studies, it has been shown that increasing the number of elements within a response results in an increase in RT (Sternberg et al., 1978). Thus, we suggested that response complexity also be defined as the number of response components within an individual response; however, a review of the task-switching literature suggests that this type of response complexity would indirectly impact switch costs via the response repetition effect.

According to past studies, the required response on an individual trial can increase or decrease RTs (e.g. Rogers & Monsell, 1995). In particular, during task-repeat trials, participants have been shown to respond faster when the previous response is repeated compared to when it is switched. Conversely, during task-switch trials, participants tend to respond slower when they are required to repeat a response compared to when they are required to switch their response. It has been suggested that this effect is due to an increase in response inhibition, which biases an individual toward the correct response when a response switch is required but biases them toward an incorrect response when a response repetition is required (Steinhauser et al., in press). Based on these previous results, we hypothesized that an increase in the number of individual response components would increase the inhibition that occurs following a response execution. This increase in inhibition would thus be more difficult to overcome, increasing the subsequent response repetition effect.

To investigate this hypothesis, we manipulated the number of individual response components by asking participants to respond with either a single-button *index* finger response or a three-button *index-ring-middle* finger response; however, our results suggested that this hypothesis was only partially supported. In particular, we were able to replicate the response repetition effect in both conditions for RTs; however, in regards to error rates, the response repetition effect was only found when a three-button response was required. It is likely that this latter effect was due to the simplicity of the single-button response, which allowed participants to respond accurately during all trial conditions. Unfortunately, our results were unable to fully support an effect of increased response complexity, although we did find a trend to suggest that increasing the number of individual response components may indeed result in increased response inhibition, producing a larger response repetition effect. Given the variability of response repetition effects in the previous research (Hubner & Druey, 2008; Meiran, 2000; Rogers & Monsell, 1995), future studies may need to utilize different experimental techniques to investigate this problem further.

Overall, our results provide some insight into the role of response complexity on task-switching behaviour. Through our results, we were able to replicate the findings of previous studies (e.g., Miller & Ulrich, 1998; Rogers & Monsell, 1994) and provide a foundation for future investigations. Although our hypotheses were not completely supported, our results do suggest that response complexity can impact task-switching costs in specific contexts. This idea is not a surprising one given that most people have found themselves in anecdotal situations in which performing multiple tasks is made more difficult by the complexity of the responses.

For instance, drivers are often faced with situations in which a rapid task-switch must occur but the required response contains multiple components or must be selected from multiple responses options. Indeed research has shown that drivers have great difficulty performing even simple additional tasks while driving (e.g., Gugerty, et al., 2004); however, very little has been done to investigate the effect of task-switching during these more complex real-world tasks. While it was hoped that the presented research would provide a foundation from which real-world applications could be made, some methodological issues may have prevented us from finding our desired results; however, our findings do suggest that more complex responses may increase task-switching costs in certain contexts. Thus, by making a few minor changes to our methodology, future researchers may be able to provide the foundation that we sought ourselves and expand our knowledge of task-switching into real-world situations.

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Figure Captions

Figure 1a: Example of a stimulus and a response for both tasks during the Single-Button condition for Experiment 1.

Figure 1b: Example of a stimulus and a response for both tasks during the Three-Button condition for Experiment 1.

Figure 1c: Example of a stimulus and a response for both tasks during the Both Button Condition for Experiment 1.

Figure 2: Mean reaction times for task repeat and task switch trials collapsed across the Single Button and Both Button conditions in Experiment 1.

Figure 3: Mean reaction times for the Single Button and Both Button Conditions (16 vs. 32 pairs) collapsed across all trial types (repeat vs. switch) in Experiment 1.

Figure 4: Mean task switch costs for the Single Button and Both Button Conditions (16 vs. 32 pairs).

Figure 5: Mean error rates for changes in the number of S-R pairs (16 vs. 32) collapsed across all trial types (repeat vs. switch) in Experiment 1.

Figure 14a-b: Mean reaction times (in milliseconds) and error rates for task repeat and task switch trials collapsed across conditions (16 vs. 32 S-R pairs) in Experiment 2.

Figure 15a: Example of a stimulus and response for the 2-Alternative Condition of Experiment 3

Figure 15b: Example of a stimulus and response for the 1-Alternative Condition of Experiment 3.

Figure 16a-b: Mean reaction times (in milliseconds) and error rates for task repeat and task switch trials collapsed across conditions (1 vs. 2 within-hand alternatives) in Experiment 3.

Figure 17a-b: Mean reaction times (in milliseconds) and error rates for 1 and 2 within-hand alternatives collapsed across all trial types (repeat vs. switch) in Experiment 3.

Figures

Figure 1a

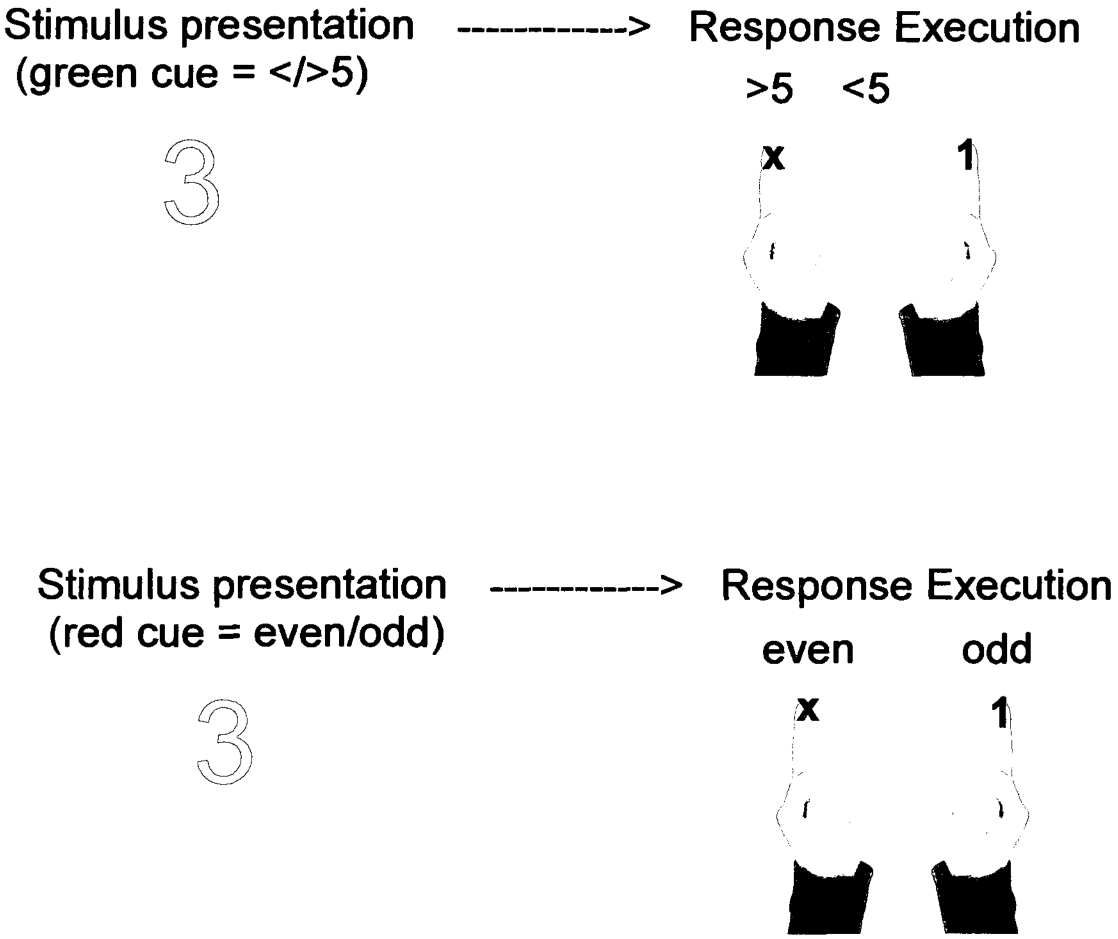


Figure 1b

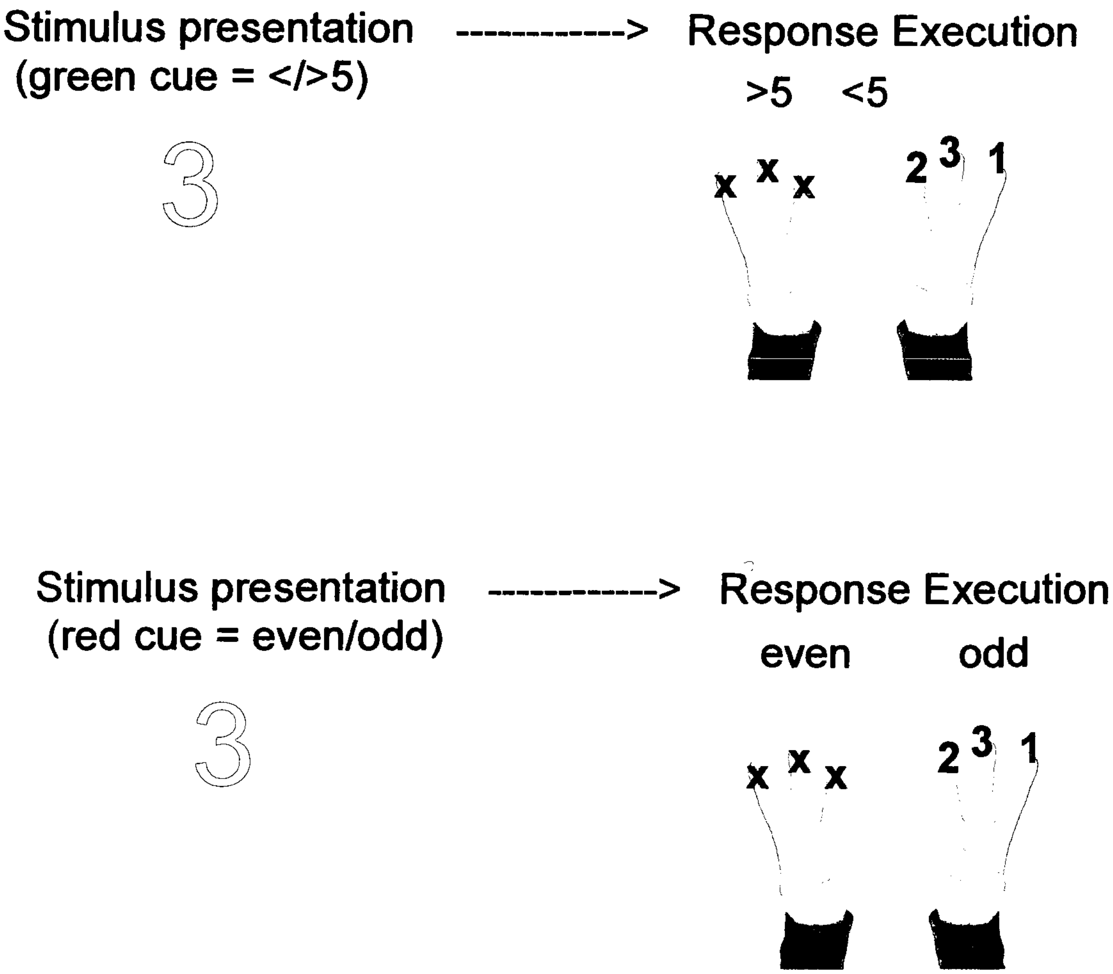

Stimulus presentation
(green cue = </>5)
------------>
Response Execution
>5 <5
3
x x x
2 3 1
Stimulus presentation
(red cue = even/odd)
------------>
Response Execution
even odd
3
x x x
2 3 1

Figure 1c

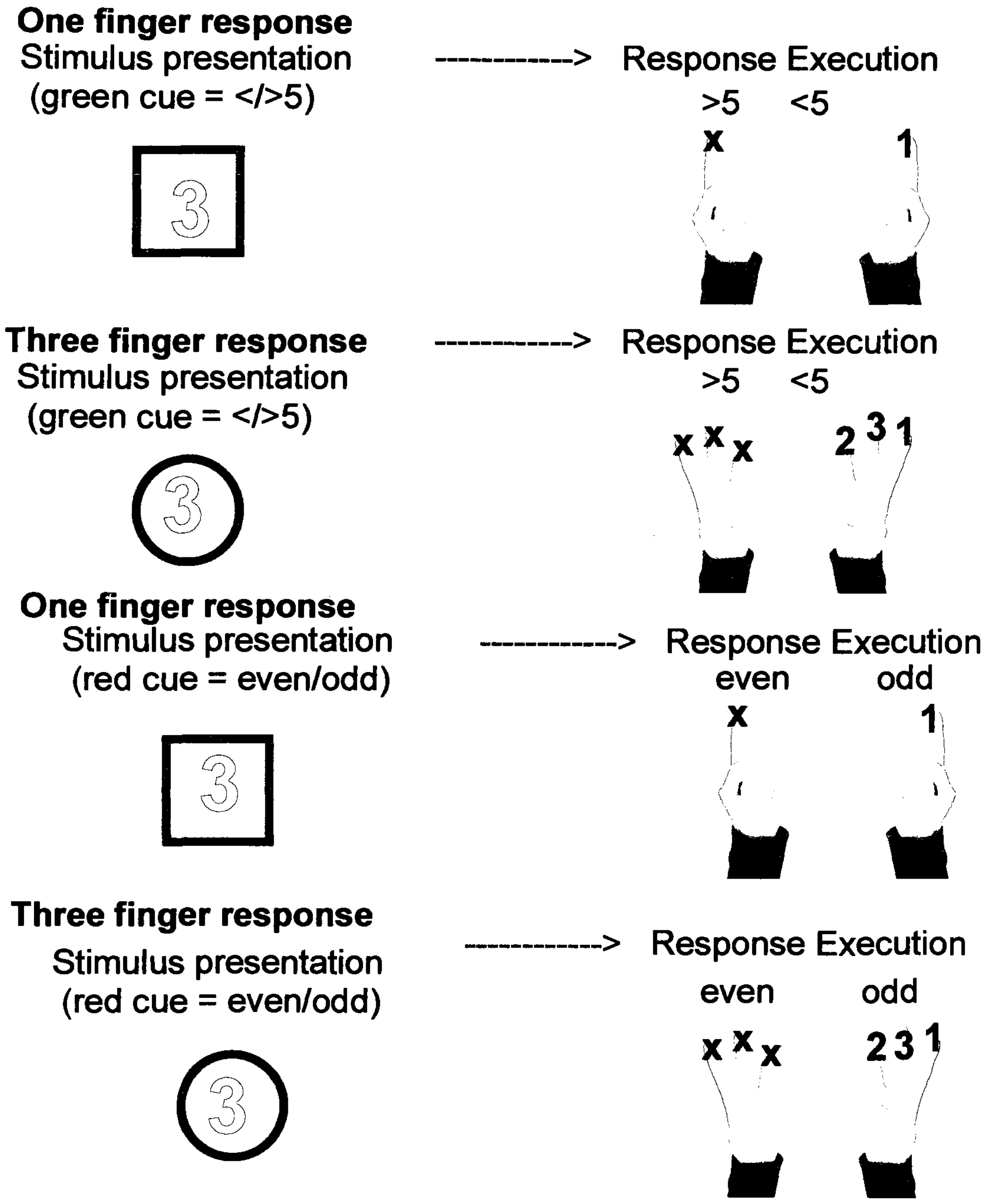

One finger response
Stimulus presentation
(green cue = </>5)
3
------------> Response Execution
>5 <5
x
1
Three finger response
Stimulus presentation
(green cue = </>5)
3
------------> Response Execution
>5 <5
x x x
2 3 1
One finger response
Stimulus presentation
(red cue = even/odd)
3
------------> Response Execution
even odd
x
1
Three finger response
Stimulus presentation
(red cue = even/odd)
3
------------> Response Execution
even odd
x x x
2 3 1

Figure 2

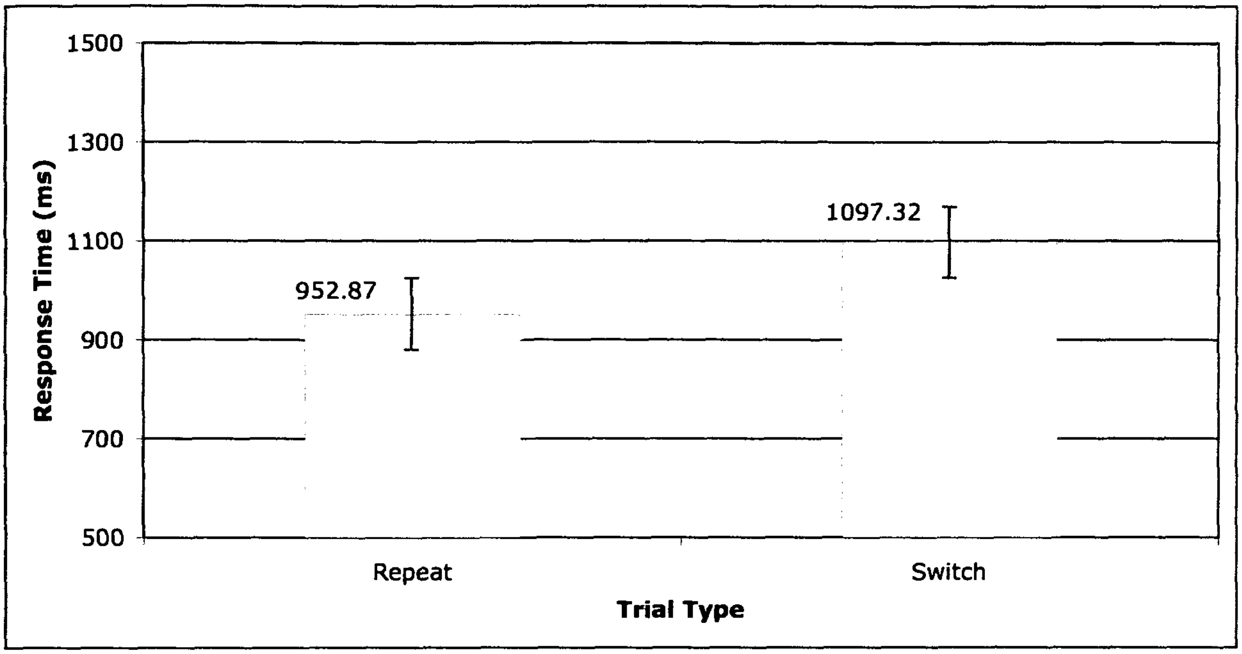

1500
1300
1100
900
700
500
Response Time (ms)
952.87
1097.32
Repeat
Switch
Trial Type

Figure 3

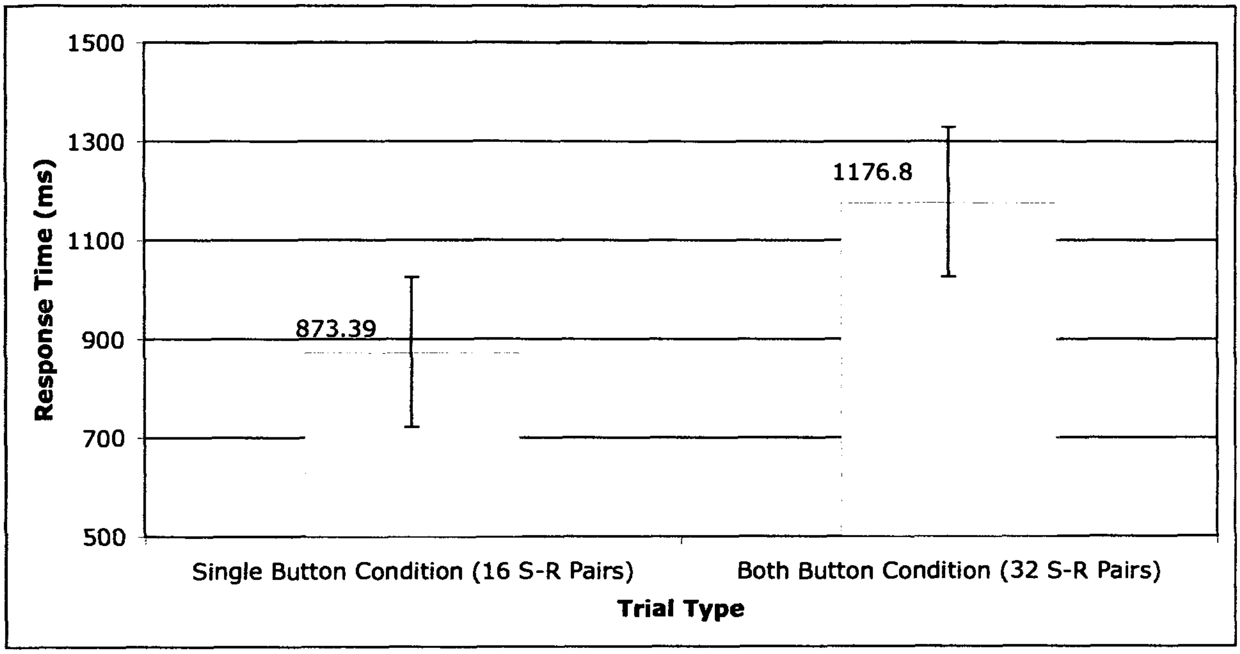

1500
1300
1100
900
700
500
Response Time (ms)
873.39
1176.8
Single Button Condition (16 S-R Pairs)
Both Button Condition (32 S-R Pairs)
Trial Type

Figure 4

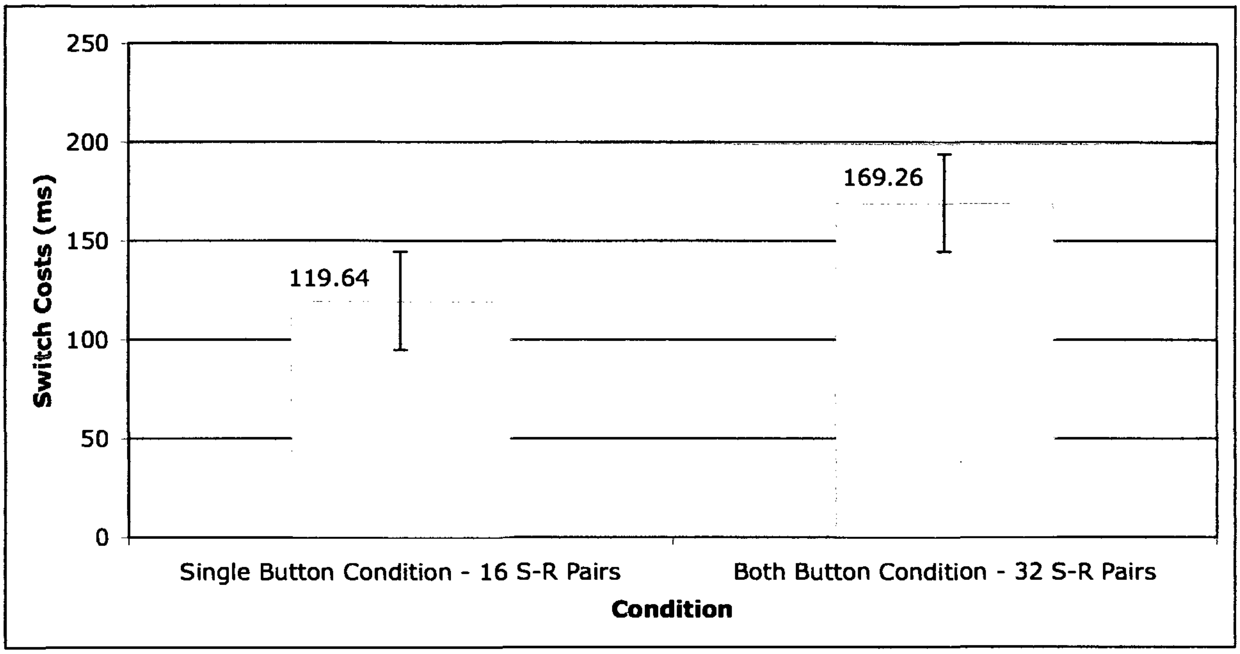

250
200
150
100
50
0
Switch Costs (ms)
119.64
169.26
Single Button Condition - 16 S-R Pairs
Both Button Condition - 32 S-R Pairs
Condition

Figure 5

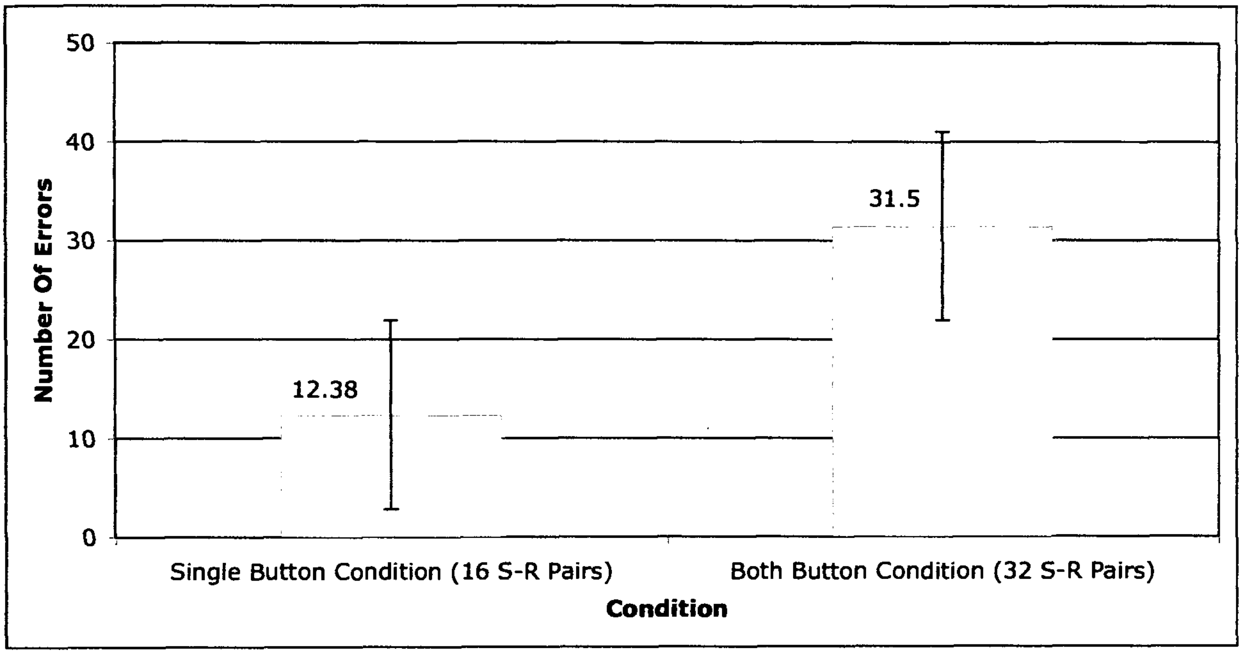

50
40
30
20
10
0
Number Of Errors
12.38
31.5
Single Button Condition (16 S-R Pairs)
Both Button Condition (32 S-R Pairs)
Condition

Figure 6

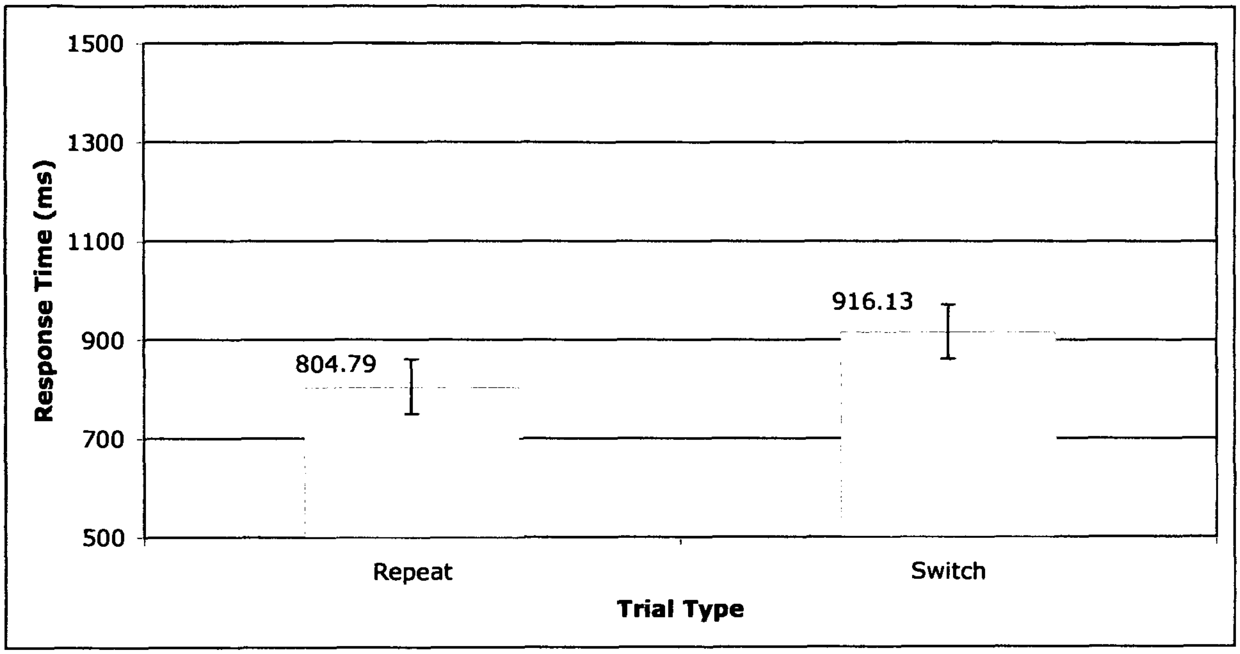

1500
1300
1100
900
700
500
Response Time (ms)
804.79
916.13
Repeat
Switch
Trial Type

Figure 7

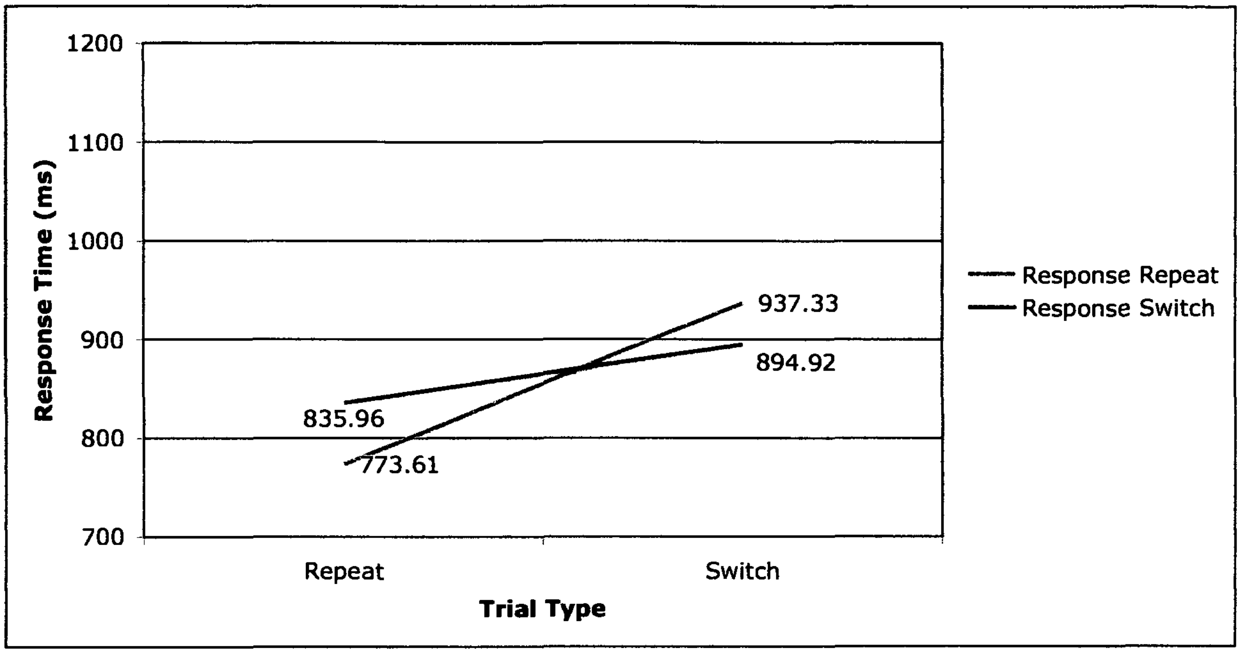

1200
1100
1000
900
800
700
Response Time (ms)
937.33
894.92
835.96
773.61
Repeat
Switch
Trial Type
Response Repeat
Response Switch

Figure 8a

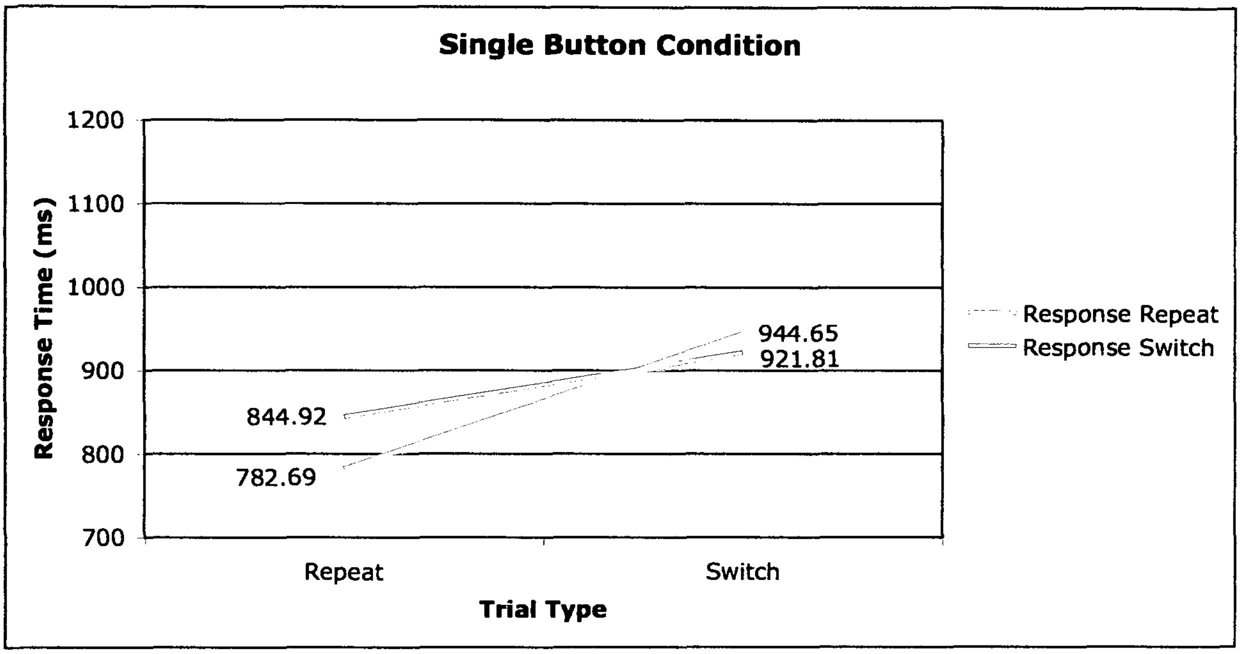

Single Button Condition
Response Time (ms)
1200
1100
1000
900
800
700
Repeat
Switch
Trial Type
844.92
782.69
944.65
921.81
Response Repeat
Response Switch

Figure 8b

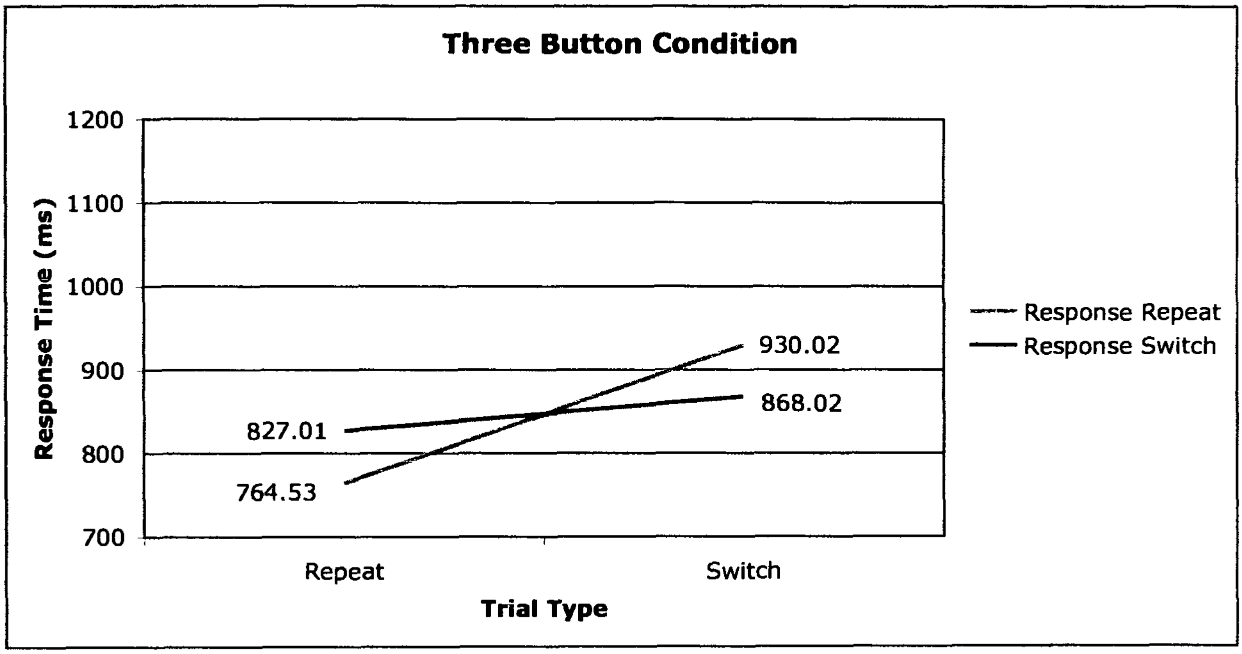

Three Button Condition
Response Time (ms)
1200
1100
1000
900
800
700
930.02
868.02
827.01
764.53
Repeat
Switch
Trial Type
Response Repeat
Response Switch

Figure 9

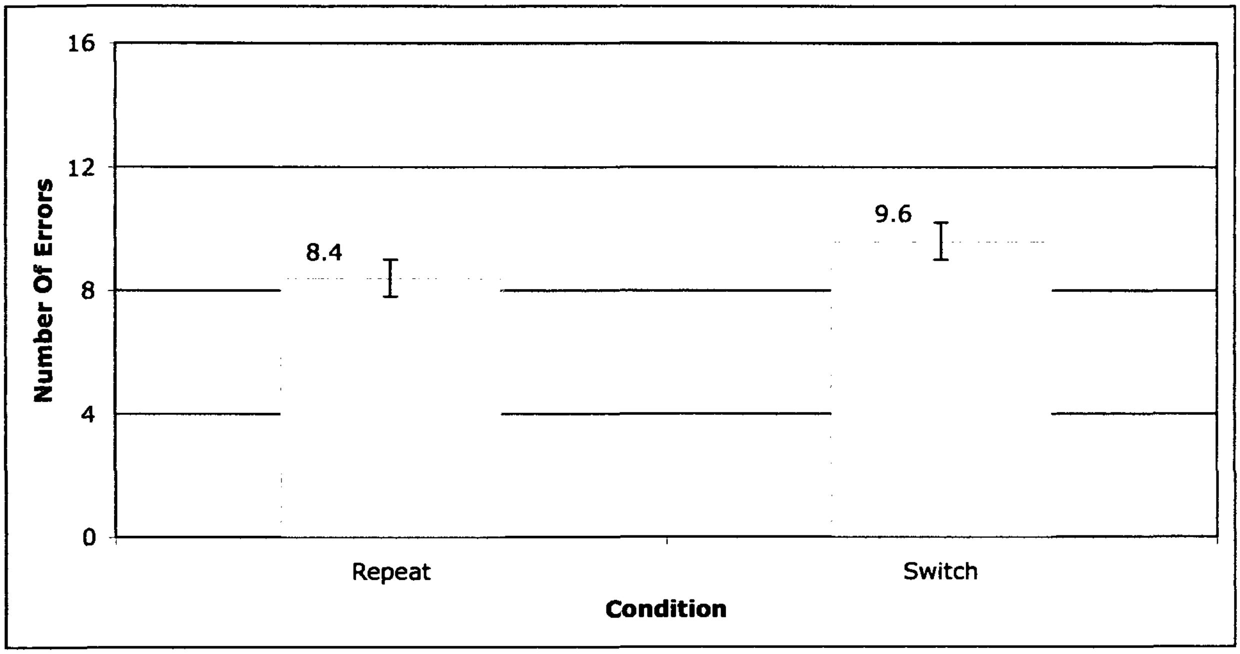


Figure 10

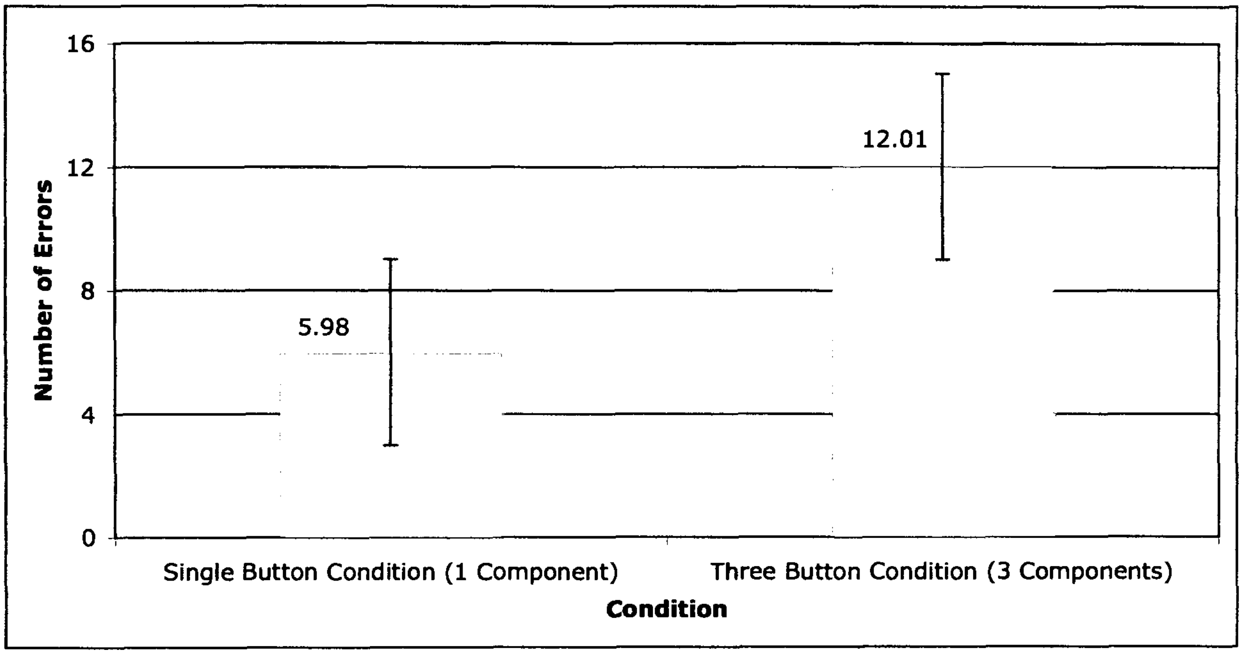

16
12
8
4
0
Number of Errors
5.98
12.01
Single Button Condition (1 Component)
Three Button Condition (3 Components)
Condition

Figure 11

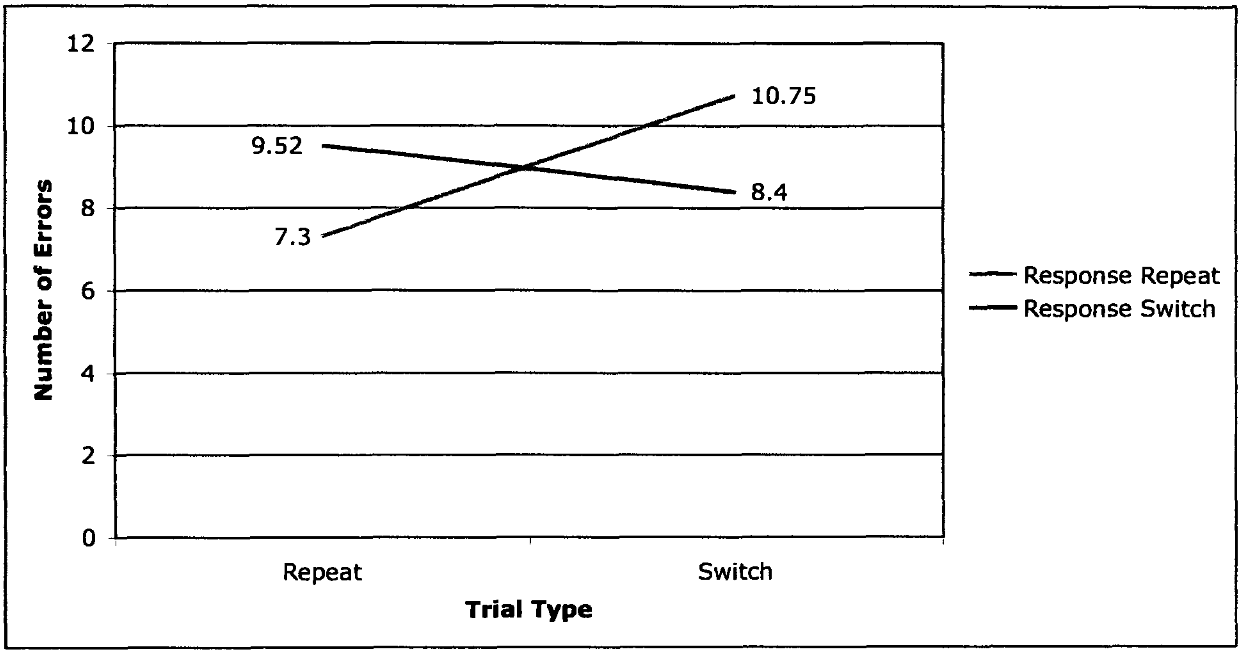

12
10
8
6
4
2
0
Number of Errors
9.52
10.75
8.4
7.3
Repeat
Switch
Trial Type
Response Repeat
Response Switch

Figure 12a

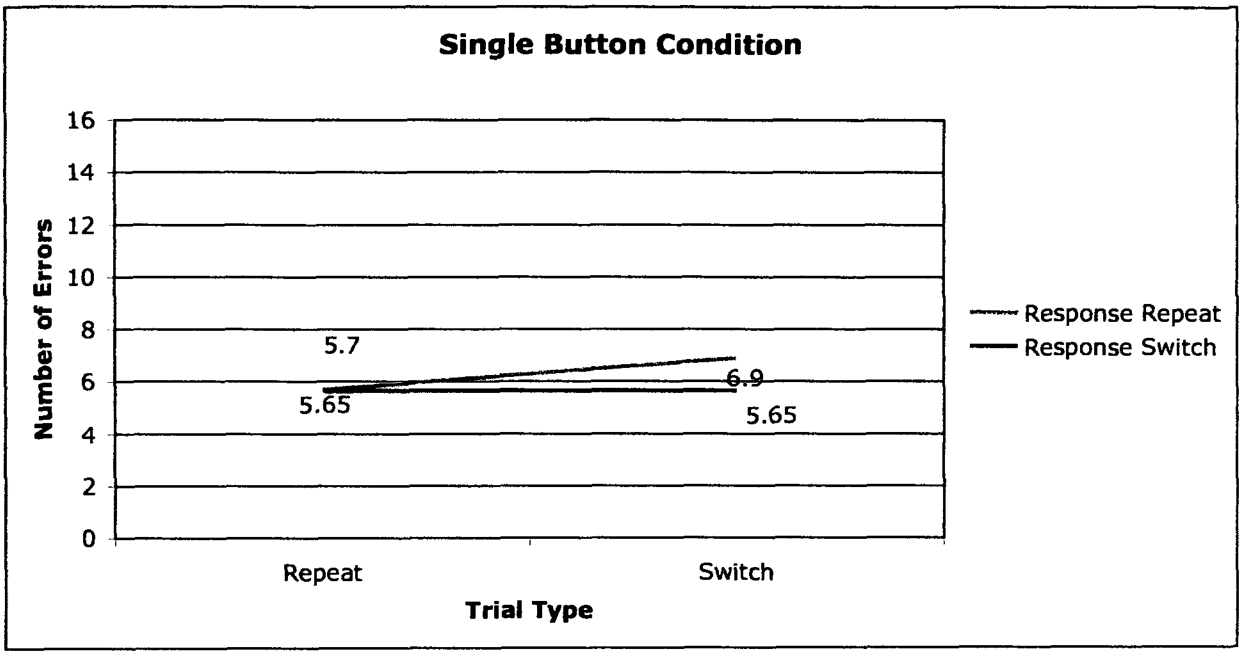

Single Button Condition
16
14
12
10
8
6
4
2
0
Number of Errors
5.7
5.65
6.9
5.65
Repeat
Switch
Trial Type
Response Repeat
Response Switch

Figure 12b

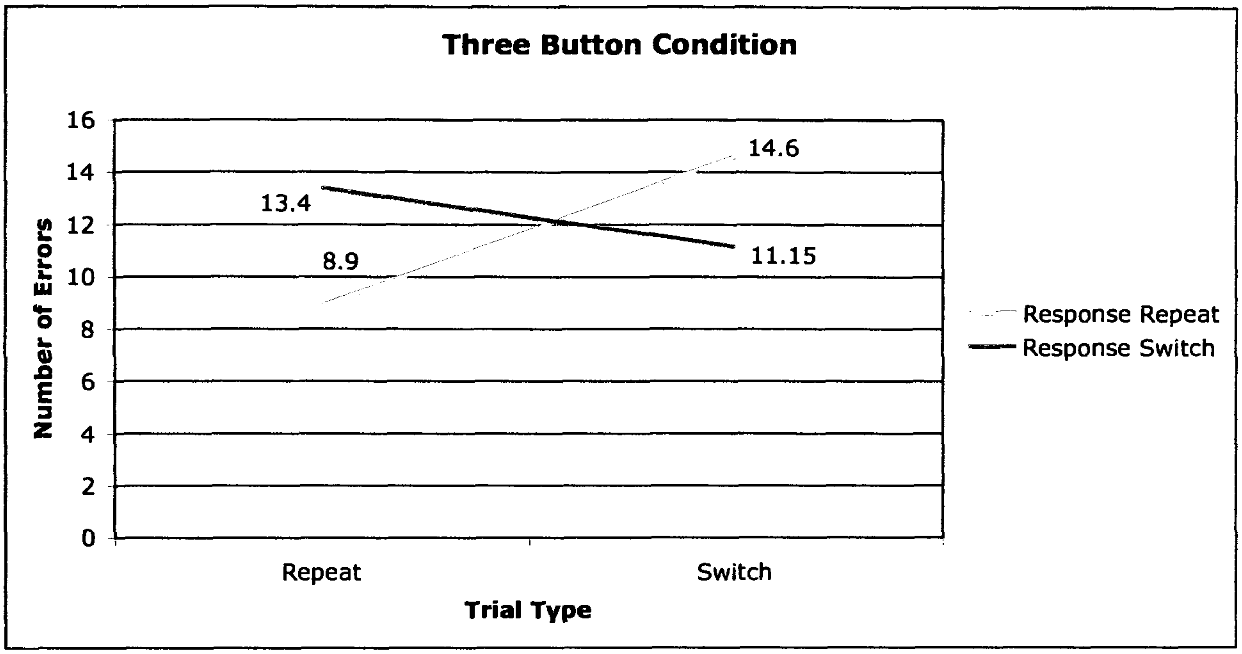
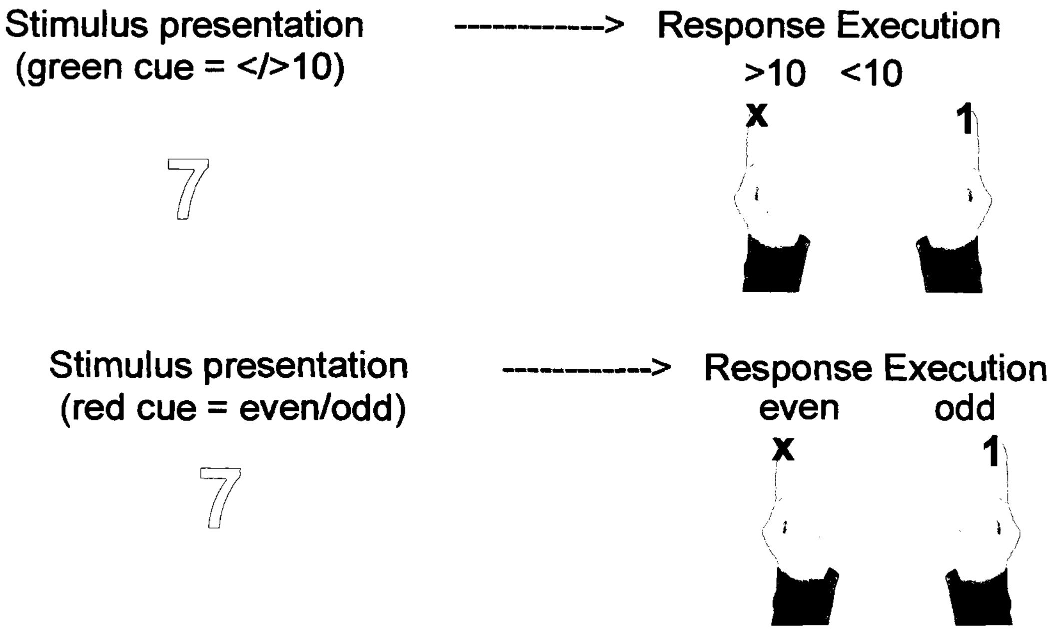

Three Button Condition
16
14
12
10
8
6
4
2
0
Number of Errors
13.4
8.9
14.6
11.15
Repeat
Switch
Trial Type
Response Repeat
Response Switch

Figure 13



Study 2 - Condition 2
- Response same as above
-32 Stimulus-Response Pairs (2-18), 1 Within-Hand Alternative

Figure 14a

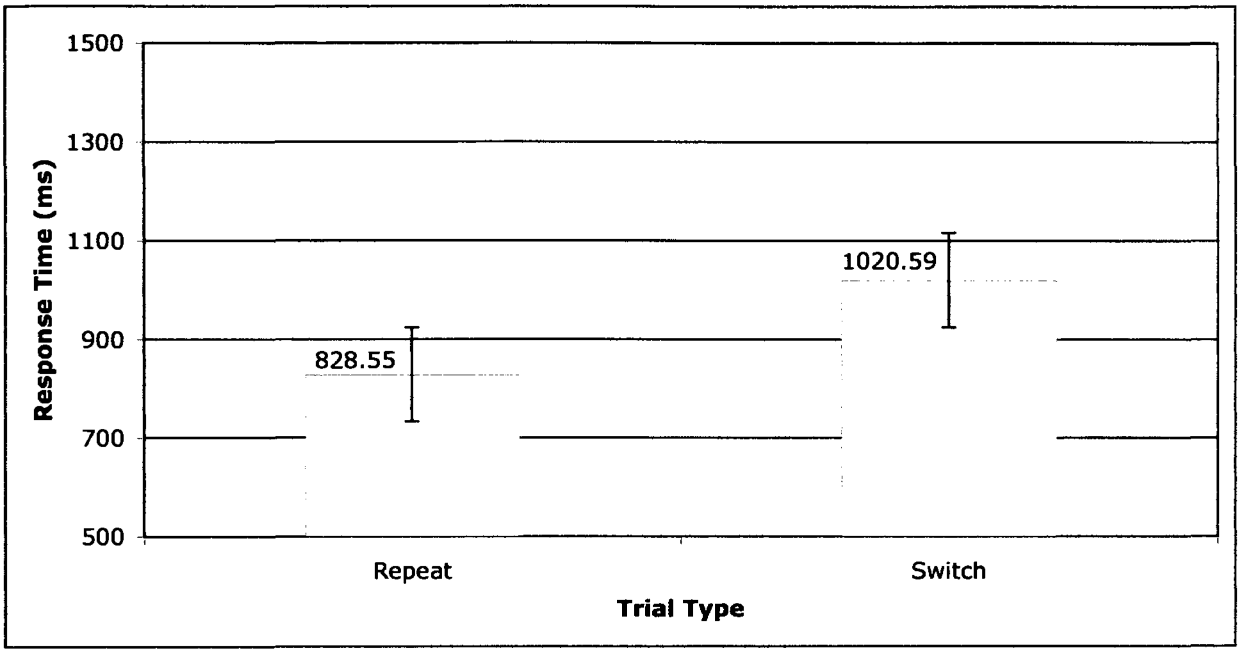

1500
1300
1100
900
700
500
Response Time (ms)
828.55
1020.59
Repeat
Switch
Trial Type

Figure 14b

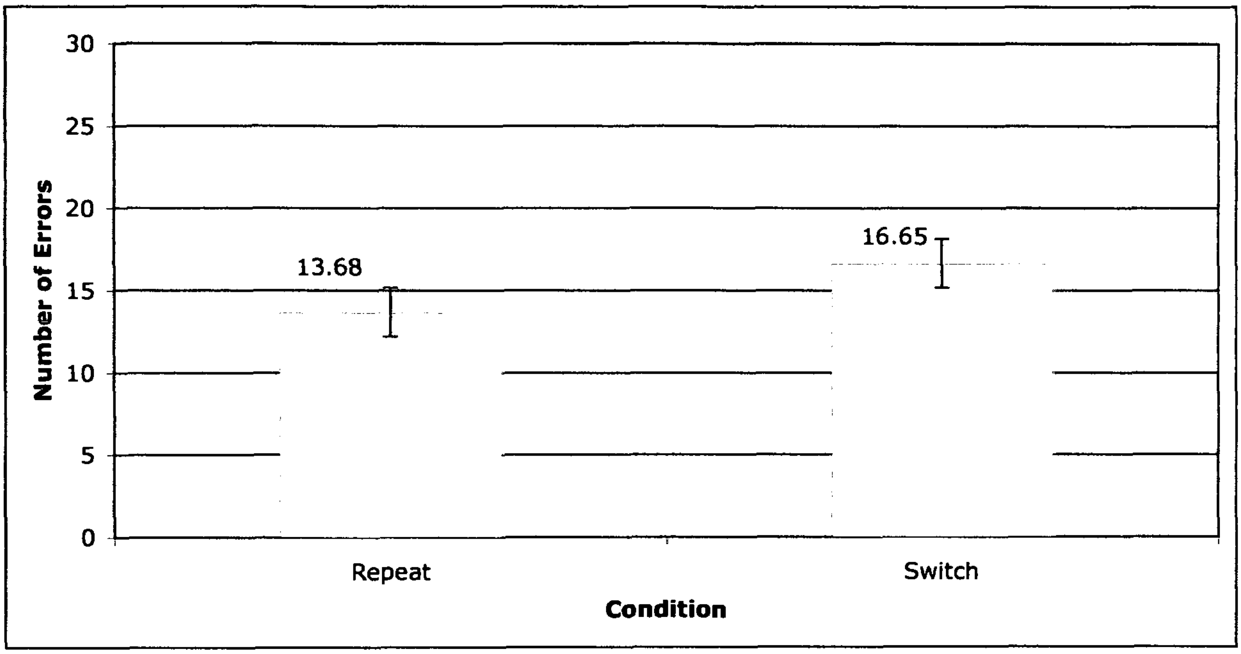

30
25
20
15
10
5
0
Number of Errors
13.68
16.65
Repeat
Switch
Condition

Figure 15a

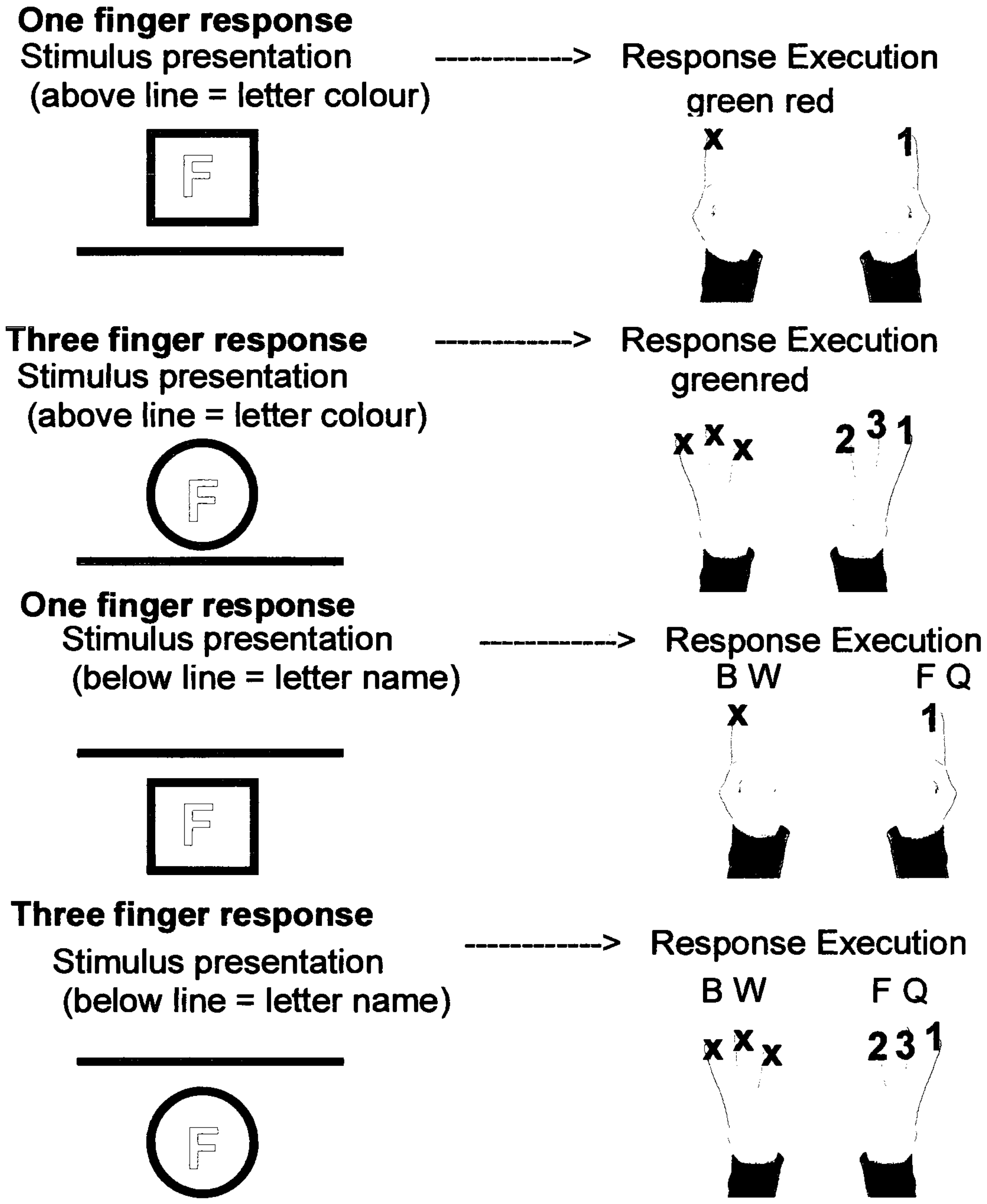

One finger response
Stimulus presentation
(above line = letter colour)
------------> Response Execution
green red
x
1
F
Three finger response
------------> Response Execution
Stimulus presentation
greenred
(above line = letter colour)
x x x
2 3 1
F
One finger response
Stimulus presentation
------------> Response Execution
(below line = letter name)
B W
F Q
x
1
F
Three finger response
------------> Response Execution
Stimulus presentation
B W
F Q
(below line = letter name)
x x x
2 3 1
F

Figure 15b

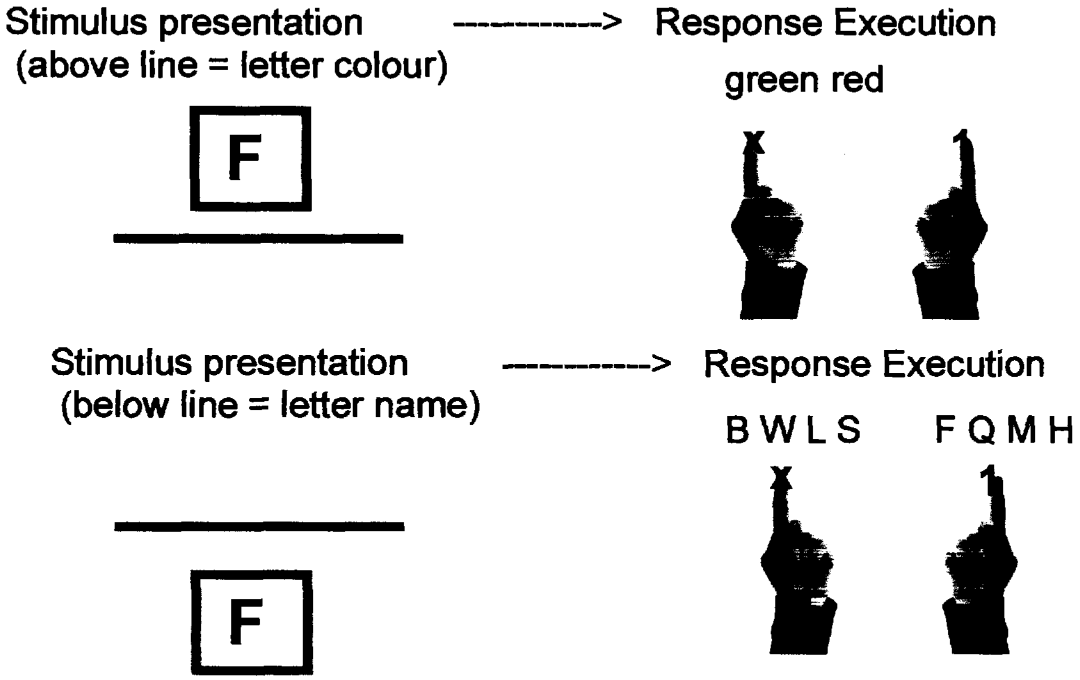
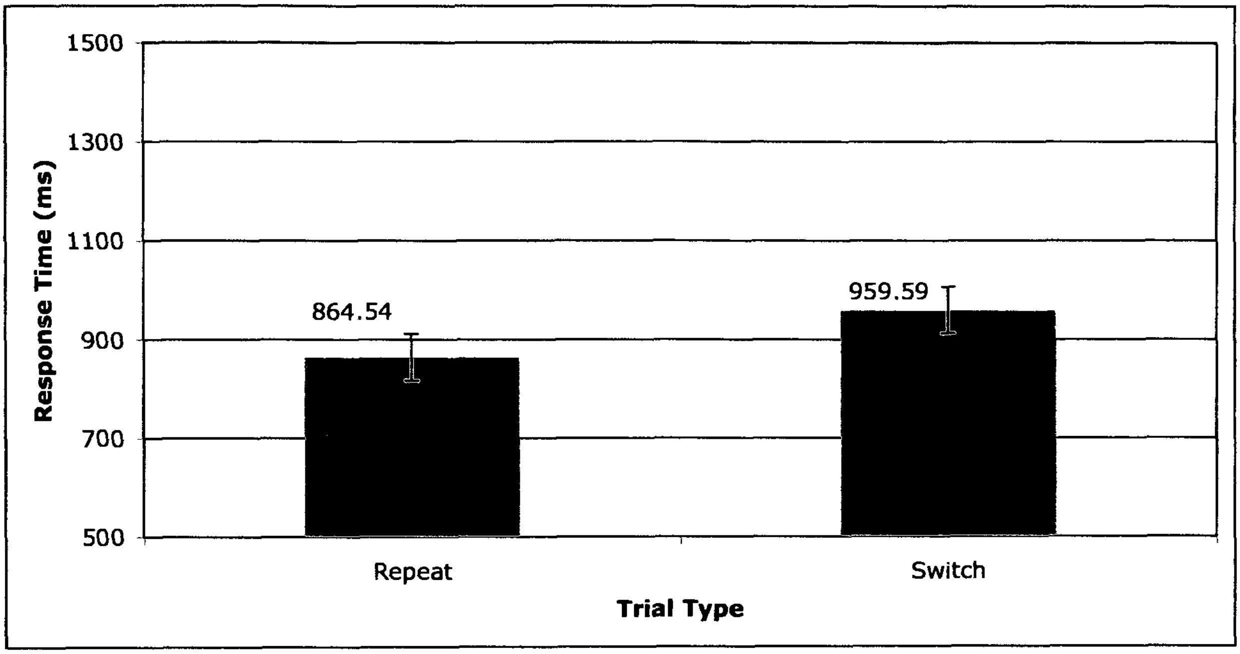

Stimulus presentation
(above line = letter colour)
----------->
Response Execution
green red
F
Stimulus presentation
(below line = letter name)
----------->
Response Execution
B W L S
F Q M H
F

Figure 16a



1500
1300
1100
900
700
500
Response Time (ms)
864.54
959.59
Repeat
Switch
Trial Type

Figure 16b

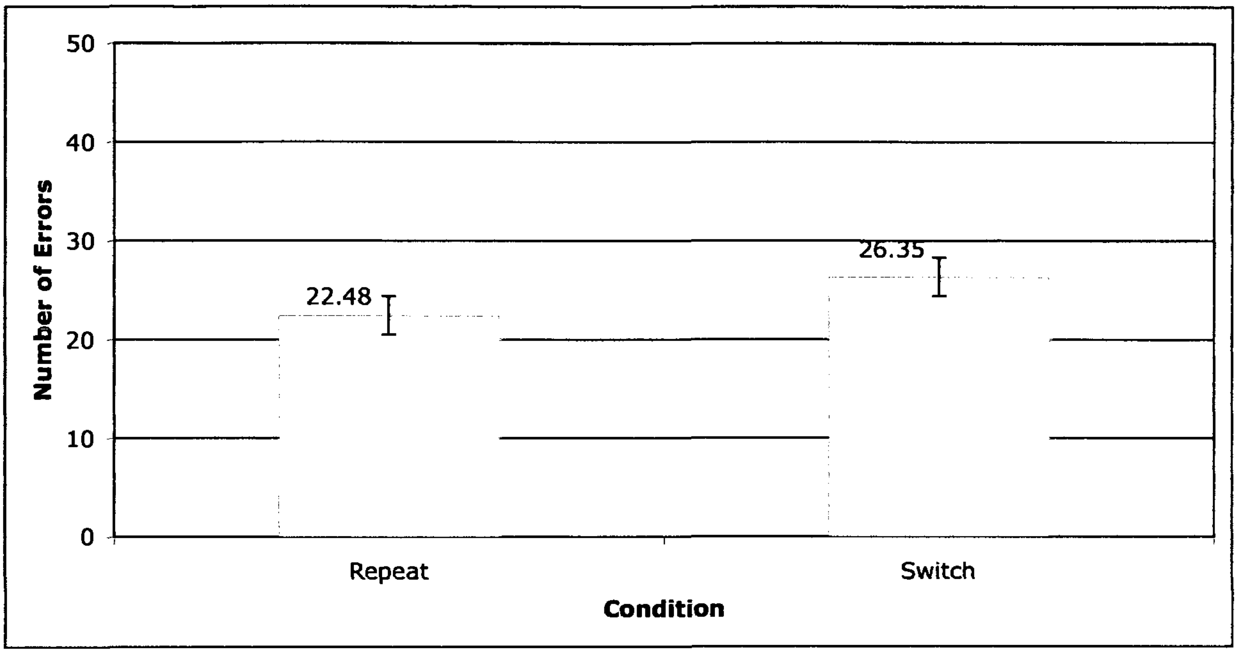

50
40
30
20
10
0
Number of Errors
22.48
26.35
Repeat
Switch
Condition

Figure 17a

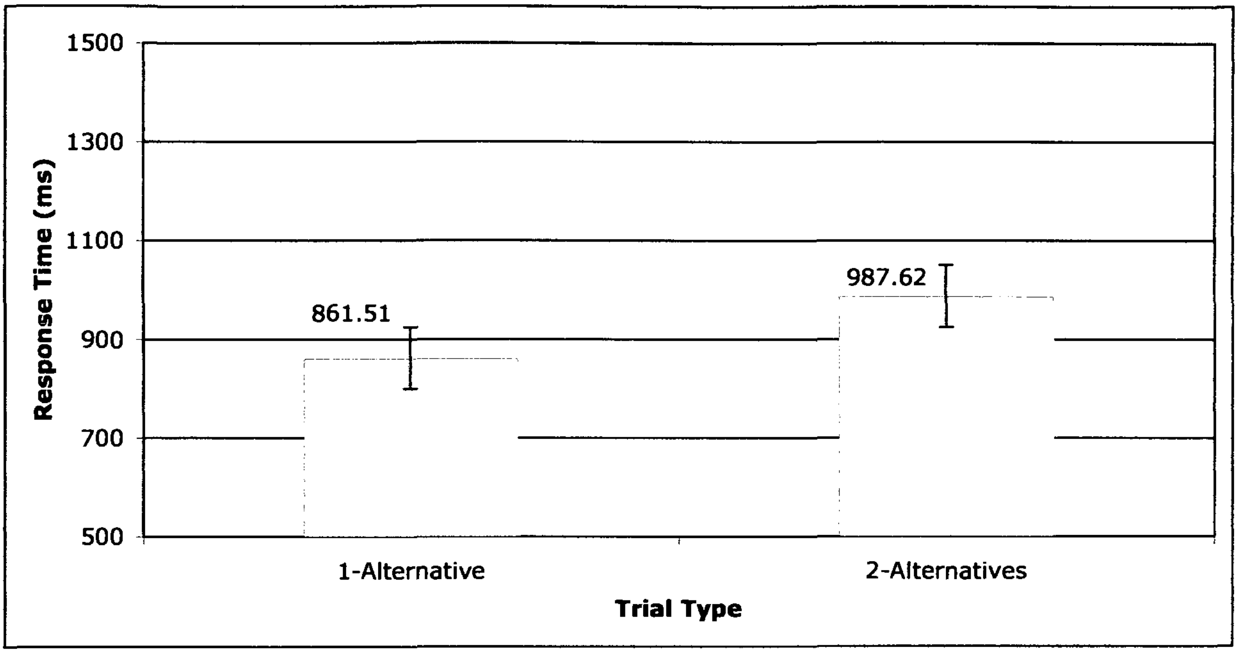
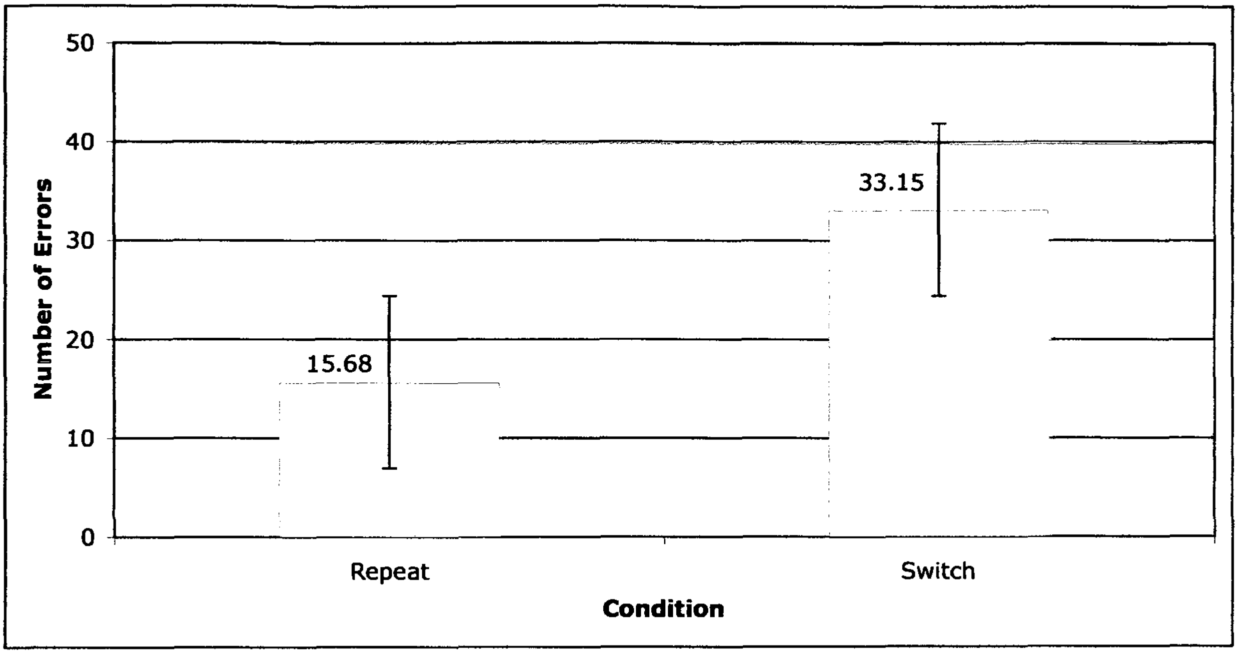

1500
1300
1100
900
700
500
Response Time (ms)
861.51
987.62
1-Alternative
2-Alternatives
Trial Type

Figure 17b


50
40
30
20
10
0
Number of Errors
15.68
33.15
Repeat
Switch
Condition