The Residual Disruption Effect in Interrupted Task Performance

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By

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ABSTRACT

THE RESIDUAL DISRUPTION EFFECT IN INTERRUPTED TASK PERFORMANCE

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A study was undertaken to identify any disruptive effects beyond the initial time to resume the primary task after an interruption, and to determine the cause of any such residual disruption effect. The first experiment demonstrated that interruptions indeed have an effect on task performance beyond the initial time to resume the task. The presence of this effect showed for the first time that the cost associated with resuming an interrupted task lasts longer than the just the resumption time. Because residual disruption effect was newly discovered, there were no ready-made explanations for it. The second experiment tested an explanation based on mediated priming in spreading activation, which maintained that the residual disruption effect was caused by higher activation levels for later goals in a hierarchical task, boosted over time as the person progresses through the task. The results showed that the effect was not due to an additive build-up of activation for future goals through mediated priming. Because the first explanation was unsupported, the third experiment considered and tested an explanation

that assumed the effect was due to the transition from memory-based performance to perceptual-based performance after an interruption. This explanation argued that interruptions cause people to revert to slower memory-based performance before resuming the faster perceptual-based performance. The results from Experiment 3 showed did not support this explanation. The fourth experiment tested the Goal History explanation, which was based on Altmann and Trafton's (2002) memory for goals framework, was centered on the number of goal retrievals from memory over time, and how goal retrieval history can result in the residual disruption effect after an interruption. The results supported the Goal History explanation by reducing the residual disruption effect when the repetition of goals, and therefore their activation history, was controlled. The empirical evidence from this set of experiments demonstrated the existence of the residual disruption effect in hierarchical tasks, and supported the Goal History explanation. Indeed, the Goal History explanation was able to account not only for the residual disruption effect, it was also able to account for the effects found in the other experiments as well.

INTRODUCTION

In this age when people are continuously connected through cell phones and other wireless communication devices, interruptions have become incessant even when working in contexts that formerly provided quiet solitude. By and large, few people are unreachable, making them susceptible to more frequent interruptions. Interruptions are disruptive in a variety of ways, but consider the processing that people go through to resume their primary task after an interruption. They have to take time to think about what they were doing, where in the task they were, and what their next action should be. This process can be characterized by the question, "now, where was I?" after an interruption.

Whereas several studies have demonstrated the obvious disruption potential of interruptions, these studies have largely focused on the characteristics of interruptions that produce disruptive effects on primary task performance (see McFarlane & Latorella, 2002 for a comprehensive review). These characteristics include interruption task complexity (Cellier & Eyrolle, 1992; Gillie & Broadbent, 1989; Speier, Valacich, & Vessey, 1999; Zijlstra, Roe, Leonora, & Krediet, 1999), similarity between interrupted and interrupting tasks (Cellier & Eyrolle, 1992; Gillie & Broadbent, 1989; Oulasvirta & Saariluoma, 2004), and the relatedness between the interrupted and interrupting tasks (Cutrell, Czerwinski, & Horvitz, 2001; Speier, Valacich, & Vessey, 1999). These disruptive effects are manifested in a variety of behaviors including increased time-on-task, longer total task times, increased decision time, decreased decision accuracy, and more performance errors. It should be noted that there is some evidence that interruptions can actually be beneficial to task performance (Miller, 2002; Speier, Valacich, & Vessey, 1992); however, the preponderance of evidence demonstrates a negative impact on primary task performance. These studies have provided important data on the disruptive nature of interruptions, but they did not specifically address the process of resuming the primary task after an interruption. This is perhaps the critical piece of information for understanding how people cognitively manage multiple tasks, specifically interruptions.

Altmann & Trafton (2002) introduced a theoretical model for the study of interruptions that specifically focuses on the time to resume the primary task after an interruption (also see Trafton, Altmann, Brock, & Mintz, 2003). The goal-activation model states that the activation levels of the cognitive representations of task goals (or subgoals) determine how quickly the primary task can be resumed after switching from the interrupting task. This resumption time, termed the *resumption lag*, has proven to be a sensitive index for the resumption of suspended goals (Altmann & Trafton, 2004; Hodgetts & Jones, 2003; Miller, 2002; Monk, Boehm-Davis, & Trafton, 2002; Monk, Boehm-Davis, & Trafton, in press; Monk, Trafton, & Boehm-Davis, in preparation; Trafton et al., 2003). For example, Monk, Trafton, and Boehm-Davis (in preparation) demonstrated that resumption lags are sensitive to the differential goal decay associated with variable interruption length, showing that previous researchers were incorrect to ignore interruption duration effects after Gillie and Broadbent (1989) failed to detect them.

Trafton et al. (2003) and Hodgetts and Jones (2003) demonstrated that prospective goal rehearsal during the period between the time when a person is notified of a pending interruption (e.g., a phone ringing) and the time the interruption is engaged (e.g., answering the call), termed the *interruption lag*, resulted in faster resumption times. From Altmann and Trafton's memory for goals framework, this indicates that when people take the time to strengthen the to-be-suspended goal prior to engaging the interruption task, post-interruption task resumption will be faster.

The recent research based on Altmann and Trafton's (2002) memory for goals framework has focused on the immediate disruptive effects of interruptions on primary task resumption; however, until recently it was unknown if there is any residual disruptive effect beyond the resumption lag. In other words, it is unknown if there are measurable effects beyond the initial resumption time, indicating that recovering from an interruption is not completely absorbed during the resumption lag. In an unpublished pilot study (see Appendix A), Monk (2003) showed an intriguing trend in the time intervals between interface actions (i.e., button clicks), termed *inter-action intervals*, in a VCR programming task. The inter-action intervals for the four-click sequence after an interruption, and when first starting the task, became shorter with each subsequent action (see Figure 1). After the initial delay in task resumption after an interruption, participants gradually decreased their response times between clicks as seen in Figure 1. Similarly, participants demonstrated increasingly faster inter-action intervals when first starting a new task. This finding indicates that there may be a residual cost beyond the resumption lag when resuming a task after an interruption, similar to when first starting a new task.

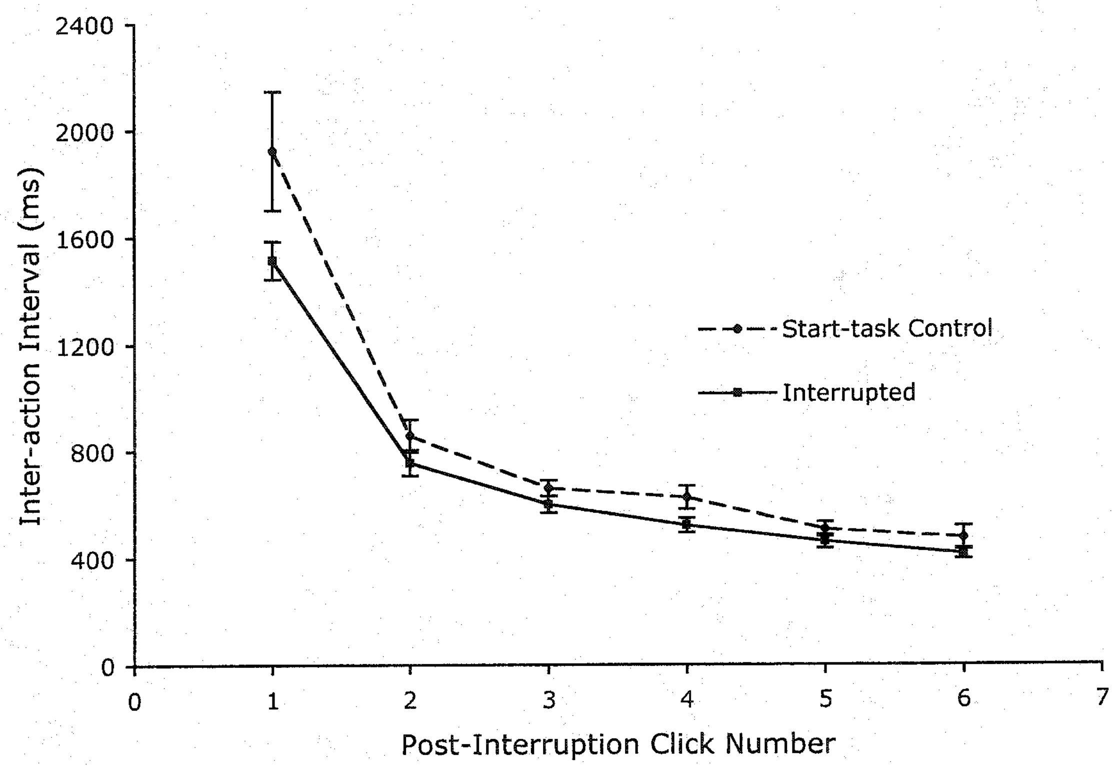

Figure 1. Monk (2003) Pilot Study Results (Residual Disruption Effect)

If the cost of an interruption was entirely captured in the resumption lag, then the subsequent inter-action intervals should have showed a relatively flat pattern. Instead, the results showed that the inter-action intervals gradually grew shorter over the course of several actions following an interruption. The faster inter-action intervals later in the sequence indicated that the earlier interface actions were slower than was possible. The delay in resuming the faster inter-action intervals after an interruption is a novel effect, which is referred to as the *residual disruption effect*.

Because the residual disruption effect was newly discovered, there were no ready-made explanations for it. The present study proposed and tests three potential explanations for the residual disruption effect. The three explanations considered as part of this study were the: (1) Activation Momentum, (2) Cognitive-Perceptual Shift, and (3) Goal History explanations. The Activation Momentum explanation was based on mediated priming (McNamara & Healy, 1988) and spreading activation (Anderson, 1983; Collins & Loftus, 1975), and argued that the current goal primes future goals beyond a single associative link in an additive fashion, creating an effect of activation build-up for future goals over time. The Cognitive-Perceptual Shift explanation argued that interruptions disrupted the rapid, perceptual-based performance level (environment-driven) achieved prior to the interruption, causing people to revert temporarily to slower, memory-based performance until they could re-transition to perceptual-based performance. The time required for this gradual transition is what caused the residual disruption effect, according to this explanation. The Goal History explanation is centered on the recency and frequency of goal retrievals from memory, and how goal retrieval history can result in the residual disruption effect after an interruption. Each of these explanations was considered independently through three experiments.

All three explanations were based on the activation-based account of memory, which states that higher levels of memory activation result in faster retrieval times. Within this theoretical framework, it was assumed that memories for goals decay over time (Altmann & Trafton, 2002; Anderson & Lebiere, 1998; Baddeley, 1986; Baddeley & Logie, 1999; Baddeley & Scott, 1971; Cowan, 1999). Although some researchers hold that goals or intentions are different from other memories (Goschke & Kuhl, 1993; Marsh, Hicks, & Bink, 1998), Anderson and Douglass (2001) showed that goals behaved no differently than other memory chunks in the Tower of Hanoi task. Therefore, goals were assumed to be equivalent to other concept nodes in declarative memory in this study. It was also assumed that increased exposure to a stimulus resulted in elevated activation levels (e.g., Stretch & Wixted, 1998). Because goals and subgoals were often repeated in hierarchical tasks, the repetition of these goals resulted in faster retrieval times due to their elevated activation levels.

Introduction To Experiments

The purpose of this study was to introduce this novel residual disruption effect for interrupted task performance, and to empirically test the predictions of three candidate theoretical explanations for the effect. The first experiment was designed to demonstrate the effect. The second experiment was designed to test predictions derived from the Activation Momentum explanation. The third experiment dealt with the predictions of the Cognitive-Perceptual Shift explanation. Finally, the fourth experiment tested the predictions of the Goal History explanation. This series of experiments used the same experimental paradigm as other recent studies testing the goal-activation model's predictions for resuming interrupted tasks (Monk, 2004; Monk, Boehm-Davis, & Trafton, 2002; Monk, Boehm-Davis, & Trafton, in press; Monk, Trafton, & Boehm-Davis, in preparation).

Experimental Paradigm

Any task can be affected by an interruption; any goal can be suspended and resumed. However, the simple tasks often associated with task switching experiments (e.g., Rogers & Monsell, 1995; Meiran, Chorev, & Sapir, 2000) do not adequately capture the task resumption process because task-switching experiments change task sets between trials rather than in the middle of trials. Hierarchical tasks include multiple goals that are often dependent on the achievement of preceding goals. These types of tasks improve the ecological validity of drawing conclusions for real-world task performance. A VCR programming task simulation was selected as the primary task for this set of experiments (see Appendix B for a detailed task analysis).

The overall goal of entering a program to record a show in the future is accomplished through a number of subgoals, each with its own set of interface actions (keystroke level goals). The subgoals are accomplished through a set sequence of interface actions. For example, the start-hour setting must be selected before adjusting the hour to the target, and then the target must be entered. It is the sequential nature of the VCR programming task that makes it especially suited for the study of interruptions. Upon resuming the programming task after an interruption, the user must recall or reconstruct the current task state and decide on the next action in the sequence, or simply recall the next action in the task sequence. The user was not forced to resume the task in the exact same point in the task; rather, the subgoal could be resumed from the beginning, after checking the last recalled entry, or at any other point in the task. However, the VCR interface afforded the user with the necessary environmental cues to quickly ascertain the current location in the task sequence, so most users were able to resume the task in sequence.

Because the focus of this study was on the residual disruption effect, it was important to select a hierarchical task with several actions under each subgoal, thus ensuring sufficient inter-action interval data after each resumption lag. The VCR task simulation is a suitable hierarchical task and has been used to study interruptions in prior research (Monk, Boehm-Davis, & Trafton, 2002; Monk, Boehm-Davis, & Trafton, in press; Monk, Trafton, & Boehm-Davis, in preparation).

In this paradigm, participants were interrupted multiple times throughout each VCR programming task trial. The onset of interruptions was based on time intervals rather than on task events (i.e., specific points in the task), or based on user control. Although McFarlane (2002) showed that forcing people to engage the interruption task produced worse primary task performance relative to when the operator had control over when to engage the interrupting task, the forced switches minimized the participant's ability to strategically link the to-be-suspended goal with environmental cues. This has been shown to reduce resumption lag (Hodgetts & Jones, 2003; Trafton et al, 2003). The current paradigm forced the participants to engage the interruption task immediately. The interruption task was a perceptual-motor tracking task that has been shown to produce disruptive effects in the VCR programming task (Monk, Boehm-Davis, &

Trafton, 2002; Monk, Boehm-Davis, & Trafton, in press).

EXPERIMENT 1

The purpose of the first experiment was to demonstrate the residual disruption effect when people performing the VCR programming task were interrupted. The presence of the effect was assessed through the inter-action intervals after each interruption. Because the data were much less stable beyond four clicks, only the first four clicks after an interruption were recorded. To provide an appropriate comparison for the interruption condition, a start-task control condition was included. In this condition, the inter-action intervals were recorded each time the participant began a new task trial. This comparison was designed to explore whether the residual disruption effect is also present when people are first beginning a new task trial.

The resumption lags in the interrupted condition should have been faster than those in the start-task control condition because the interrupted goals should have had some level of activation due to prior retrievals. In contrast, the goals in the start-task control condition should not have been recently retrieved to help boost activation for a subsequent retrieval.

Method

Participants. Twenty undergraduates from George Mason University received course credit for participating in this experiment. Fourteen women and six men participated and ranged in age from 17 to 40, with an average age of 20 years.

Materials. The primary task was to program a VCR using a simulated VCR built in Macintosh Common Lisp. The VCR interface, originally designed for experimental use (Gray, 2000; Gray & Fu, 2001), was not based on a commercially available VCR. The interruption task was a pursuit-tracking task that required subjects to track a moving target with the computer mouse. The VCR and interruption tasks were presented side-by-side on a Macintosh G4 computer with a 17-inch VGA monitor. The VCR task was on the left side of the monitor and the tracking task was on the right side. Both tasks required only the computer mouse, and only one of the tasks was visible at a time.

VCR task. Programming a show consisted of four tasks: entering the show's start-time, end-time, day of week, and channel number. Two of these four tasks were broken down further into subtasks. There were three subtasks for the start-time (start-hour, start-10min, and start-min) and three for the end-time (end-hour, end-10min, and end-min). The day-of-week and channel tasks contained no subtasks and therefore were considered to be equivalent to the subtask level rather than the task level. A detailed task analysis of the VCR task is available in Appendix B.

To better understand the steps involved in carrying out these subtasks, a description of entering the start-time is presented (see Figure 2). To enter the start-time, the participant first clicked the Column button above the hour buttons (leftmost square button). This signified the beginning of the start-hour subtask. The participant then clicked the Start-hour button, and clicked on the Up or Down arrow multiple times until the displayed hour number reached the target hour. Next, the participant clicked on the

Enter button to save the start-hour setting. Finally, to end this subtask, the participant clicked the Column button again (to "deselect" it) before moving onto the next subtask.

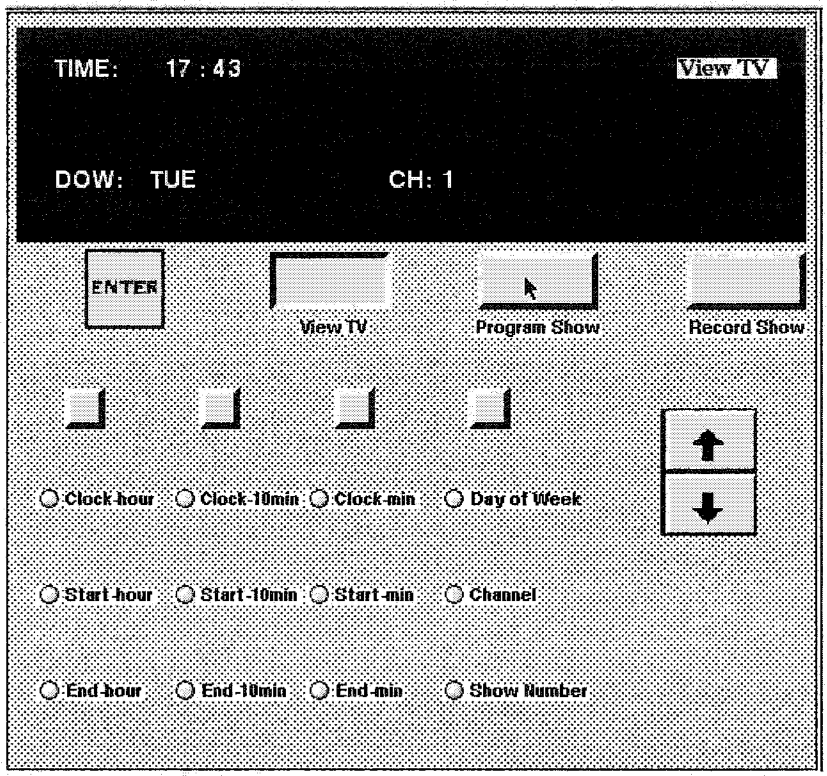

Figure 2. Simulated VCR Interface.

The participant was required to repeat the same steps for the start-10 minute and start-minute settings to complete the start-time entry. The same process was completed for the end-time, day-of-week, and channel number entries, respectively. The VCR display was blank when no setting was selected. The participants had access to target show information (the show name, start-time, end-time, day-of-week, and channel number) at all times as the information was posted to the right of the monitor on a 3x5 index card.

Interruption task. The interruption consisted of a pursuit-tracking task. The tracking task required the participant to track an airplane (target) moving around the right half of the screen in a random pattern.

Design. The experiment was a single factor repeated measures design with two conditions: interrupted trials and start-task control trials. The primary dependent measure was the inter-action interval, which was defined as the time elapsed between the mouse clicks in the interface. The time between the offset of the interruption and the first mouse-click on a VCR button was the resumption lag measure. The inter-action intervals were measured for the first four clicks after each interruption or task start. The post-resumption inter-action interval pattern consisted of clicks 2 through 4 after an interruption (click 1 defines the resumption lag). Each participant completed five interrupted and five control trials. Each control trial consisted of five shorter trials where the participant began the VCR programming task at a different point in the task and programmed only the start- or end-time component. Participants alternated between one interrupted trial and one set of start-task control trials.

Procedure. Each participant was tested individually. The sessions, which lasted approximately one hour, began with the experimenter explaining the VCR task through a demonstration. The participants were then given two practice trials with the VCR task without interruption. After completing the VCR task practice trials, the participants were given two 60-second practice trials with the tracking task. The participants were then introduced to the interruption condition, where they alternated performing the VCR and interruption tasks. The participants were told that the cursor position for each respective task would be saved and reset upon each switch so that dragging the mouse back and forth between the two sides would be unnecessary. Resetting the cursor position with each switch to the VCR task eliminated problems with carry-over cursor movements from the tracking task. The two tasks were essentially paused when not active. After the two practice interruption trials, the participants completed the experimental trials, each with new show information to be programmed. For each trial, participants began by programming the VCR. Interruptions occurred every 10 seconds and lasted for 5 seconds, creating a back-and-forth sequence between the VCR and interruption task in an interlaced fashion until the VCR program entry was completed. After completing the 10 experimental trials, the participants were debriefed and dismissed.

Results and Discussion

The analyses were restricted to those that addressed the specific goal of demonstrating the presence the residual disruption effect in the post-resumption inter-action interval pattern. Figure 3 shows the mean inter-action interval patterns for the control and interruption conditions. The linear trend for post-resumption inter-action intervals (clicks 2 through 4) was indeed significant, $F(1, 19) = 42.88$, $p < .0001$, $MSE =$ 22,150. All paired comparisons between the three points were significant ($p < .001$), showing that the inter-action intervals were faster with each successive click.

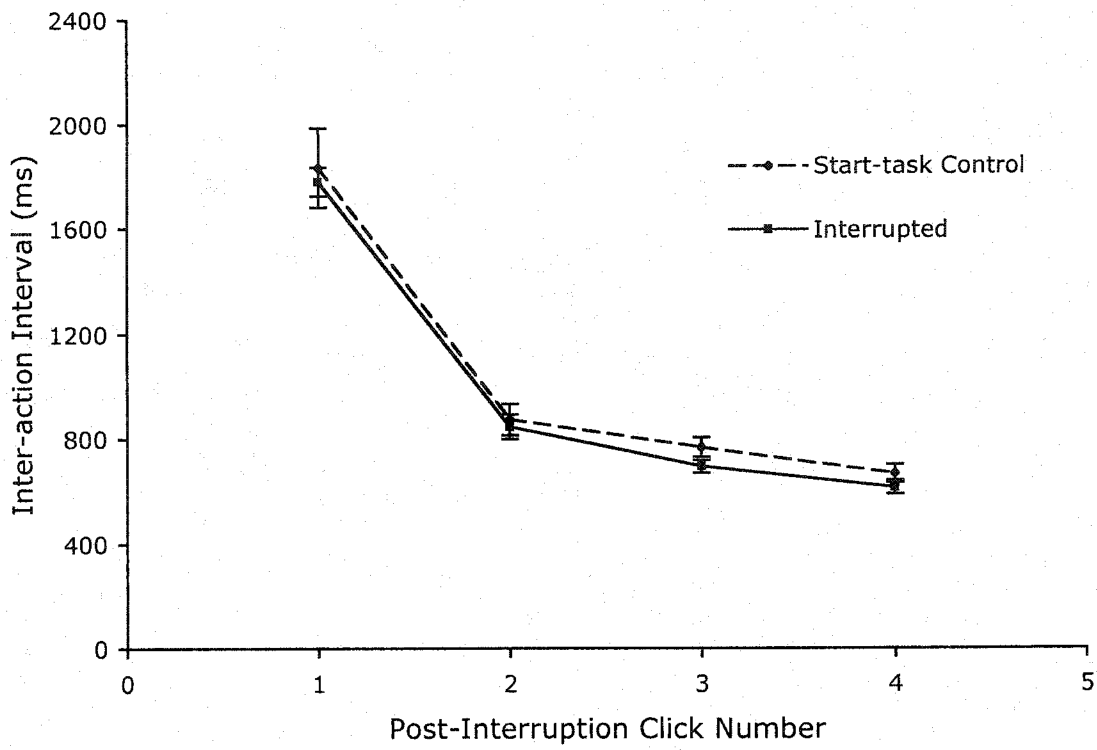

Figure 3. Inter-action Interval Results for Experiment 1.

Before concluding the presence of a residual disruption effect, it was necessary to first show that the general inter-action interval pattern was different from the post-resumption speed-up trend seen in clicks 2 through 4 of Figure 3. It was assumed that inter-action intervals would stabilize over time, and that performance would eventually return to this stable level after an interruption. This assumption was based in part on task switching evidence from Kramer, Hahn, and Gopher (1999) that showed flat response times for trials before and after the task switch delay (i.e., switch cost). To assess whether the pre-interruption inter-action interval pattern was different than the post-resumption data from the interruption condition, the inter-action interval pattern just prior to each interruption was examined.

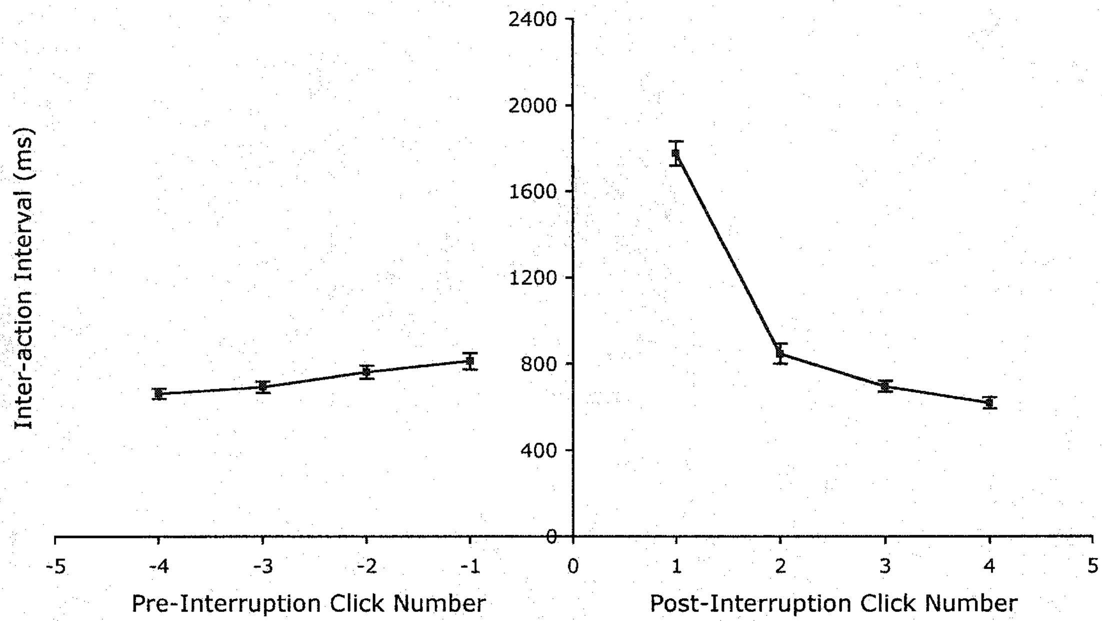

Figure 4. Pre- and Post-Interruption Inter-action Intervals.

As is evident from Figure 4, the four clicks prior to an interruption showed a steady increase in inter-action intervals that was shown to be a significant linear trend, $F(1, 19) = 18.30, p < .001, MSE = 15{,}139$. Whereas the post-resumption data showed a speed-up pattern, the pre-interruption data showed a slow-down trend. The interaction between the linear trends was significant, $F(1, 19) = 28.44, p < .001, MSE = 21{,}707$, indicating that the two trends had reliably different slopes. The slow-down trend in the pre-interruption inter-action intervals may have been due to an anticipation of the impending interruption. In other words, because the interruptions occurred every 10 seconds, the participants may have learned to slow down in anticipation of the next interruption. The clear difference between the pre-interruption and post-resumption inter-action interval patterns strongly supports the presence of the residual disruption effect in the post-resumption data.

The mean inter-action intervals were shorter when the participants were interrupted compared to when they started a new trial (control condition), $F(1, 19) = 4.61$, $p < .05$, $MSE = 17{,}265$. The inter-action intervals continued to get faster with each successive click in both the interruption condition, $F(1, 19) = 27.84$, $p < .001$, $MSE = 18{,}975$, and control condition, $F(1, 19) = 26.73$, $p < .001$, $MSE = 15{,}870$. The interaction between the two slopes was not significant, $F(1, 19) = .225$, indicating that the residual disruption effect shared a similar slope regardless of condition. This suggests that resuming a task after an interruption is very much like starting a new task, at least in terms of inter-action intervals.

To test the prediction that the mean resumption lag for the interrupted condition would be faster than the mean start-up lag in the control condition, the two lags were compared. The mean resumption lag for the interrupted condition was numerically shorter than the lag in the task-start control condition ($M = 1778$ ms, $SD = 252$, and $M = 1833$ ms, $SD = 683$, respectively); however, this difference was not significant, $F(1, 19) = .161$. This finding did not support the predictions based on the goal-activation model; however, it did show a trend in the predicted direction.

The results of Experiment 1 successfully demonstrated the presence of the residual disruption effect in interrupted task performance. The inter-action intervals grew faster with each successive click, indicating higher activation levels for the later goals. The resumption lag results did not show a difference between the interruption and start-task control conditions. This finding did not support the prediction; however, the inter-action intervals were slightly faster for the interruption condition, which is consistent with the predicted outcome. Notably, both conditions showed the same pattern of response times for the click sequence following an interruption. This finding indicates that resuming a task after an interruption is very similar to starting the task anew in terms of inter-action intervals. The next three experiments explore different explanations for this effect.

EXPERIMENT 2

The second experiment was designed to test the predictions of the Activation Momentum explanation of the residual disruption effect. The Activation Momentum explanation attempted to account for the residual disruption effect through growing levels of activation for later goals in a hierarchical task. This explanation argued that as people progressed through a hierarchical task, the activation levels for each subsequent task goal grew in an additive fashion. The build-up of activation over time for the later subgoals in a hierarchical task was much like a ball gaining speed as it rolls farther down a hill—it gained momentum as it rolled. Similarly, the subgoals in a task hierarchy gained activation momentum as the task progressed. In the case of the residual disruption effect, this implied that each subsequent goal had an increasingly higher level of activation, which resulted in faster responses for each successive action over time. This created the speed-up trend that characterized the residual disruption effect. The question was how did the subsequent goals gain increasing levels of activation?

The Activation Momentum theory posits that the additive build-up of activation for later goals is accomplished through associative priming. Associative priming is a robust effect in which the response to a target word is faster and more accurate when it is preceded by a related word. Spreading activation theory (Anderson, 1983; Collins & Loftus, 1975) is one of the principal accounts of this effect. According to the theory, concepts are represented as nodes in declarative memory and these nodes are connected to related nodes via links, creating a vast associative network of concepts in memory. The amount of activation spread is partly determined by the strength of the link between nodes (Cañas, 1990; de Groot, Thomassen, & Hudson, 1982), which is defined by the strength of the relationship between concepts. The subgoals in a hierarchy must share reasonably strong links in order for activation to grow at a consequential rate.

In order for the additive build-up of activation to occur, the associative goal network must assume a task-level goal that acts as a mediator in the spreading of activation to subsequent subgoals. There is considerable evidence demonstrating the existence of mediated priming (McNamara & Healy, 1988), ranging across tasks such as cued recall (Nelson, Bennett, & Leibert, 1997; Nelson, McKinney, Gee, & Janczura, 1998), word naming (Balota & Lorch, 1996), and lexical decision (Bennett & McEnvoy, 1999; McNamara, 1992). The Activation Momentum explanation relies on mediated priming to explain the additive build-up.

For example, the goal of washing clothes involves several subgoals: putting clothes in the washer, adding laundry detergent, selecting washer settings (e.g., cold water, gentle cycle), and starting the washer. The task-level goal of "doing the laundry" is instantiated as a node in memory with connections to the subgoals of adding clothes, adding detergent, selecting the wash settings, and starting the cycle. When the focus of attention is on the first subgoal of adding cloths to the washer, activation is spread to the subsequent subgoals through the "doing the laundry" task-level goal. Because activation spreading is additive, the activation levels for the later subgoals will continue to grow as the task progresses through the subgoals. The increasingly elevated activation levels for subsequent goals result in faster retrieval times, and therefore response times. Thus, the activation momentum that is produced through spreading activation explains the residual disruption effect.

The Activation Momentum explanation makes specific predictions about the activation levels for each step or operation in a hierarchical task like the VCR task. Because the theory argues for increasing activation for each subsequent task operation, faster resumption lags for interruptions occurring later in the task compared to interruptions occurring earlier in the task should result. Early in the task sequence, the activation levels for each subtask goal are just beginning to grow stronger while the activation levels for the later subtask operations have had the opportunity to grow much higher than the earlier subtask stages. This is a necessary prediction of the Activation Momentum explanation. To test this prediction, the resumption lags for interruptions occurring early in the task were compared to resumption lags for interruptions occurring late in the task.

A second consequence of this theory is that the higher levels of activation for the later task operations should affect not only the initial resumption lag, but also the subsequent inter-action interval pattern. Whereas the slopes of the trends was expected to be similar between the early and late interruptions, as it was between the interruption and control conditions in Experiment 1, the late interruption condition should result in faster inter-action intervals overall.

Method

Participants. Fourteen undergraduates from the George Mason University psychology subject pool participated in this study as a course requirement. Five men and 9 women participated; they ranged in age from 17 to 25, with an average age of 19.5 years.

Materials. The VCR and interruption tasks were identical to those used in Experiments 1 and 2.

Design. The experiment was a single factor within-subjects design with two levels of interruption timing. Rather than having repeated interruptions as in the first two experiments, there was only one 5-second interruption during each VCR programming trial. The interruption occurred 10 seconds into the trial in the early condition, and 30 seconds into the trial in the late condition. The measures were the same as those used in the previous experiments.

Procedure. The procedure was identical to that in the first experiments except that each participant experienced only one interruption while programming the VCR. Each participant was exposed to both the early and late interruption conditions during the two interrupted practice trials. Participants completed 20 experimental trials, each with new show information to be programmed. Half of the trials were early interruption trials and the other half consisted of late interruption trials. Trial order was randomized for each participant.

Results and Discussion

As seen in Figure 5, the mean resumption lag for the early interruption condition (*M* = 1975 ms, *SD* = 357) appears to have been slightly faster than the mean resumption lag for the late interruption condition (*M* = 2111 ms, *SD* = 524). However, a repeated-measures ANOVA showed that this difference was not significant, $F(1, 13)=1.07$, $p = .319$, *MSE* = 121,437. Clearly this result stands in contrast to the predictions for the resumption lag results. Although no conclusions can be drawn from a null effect, the fact that the means did not even trend in the direction predicted by the Activation Momentum explanation does not support the explanation.

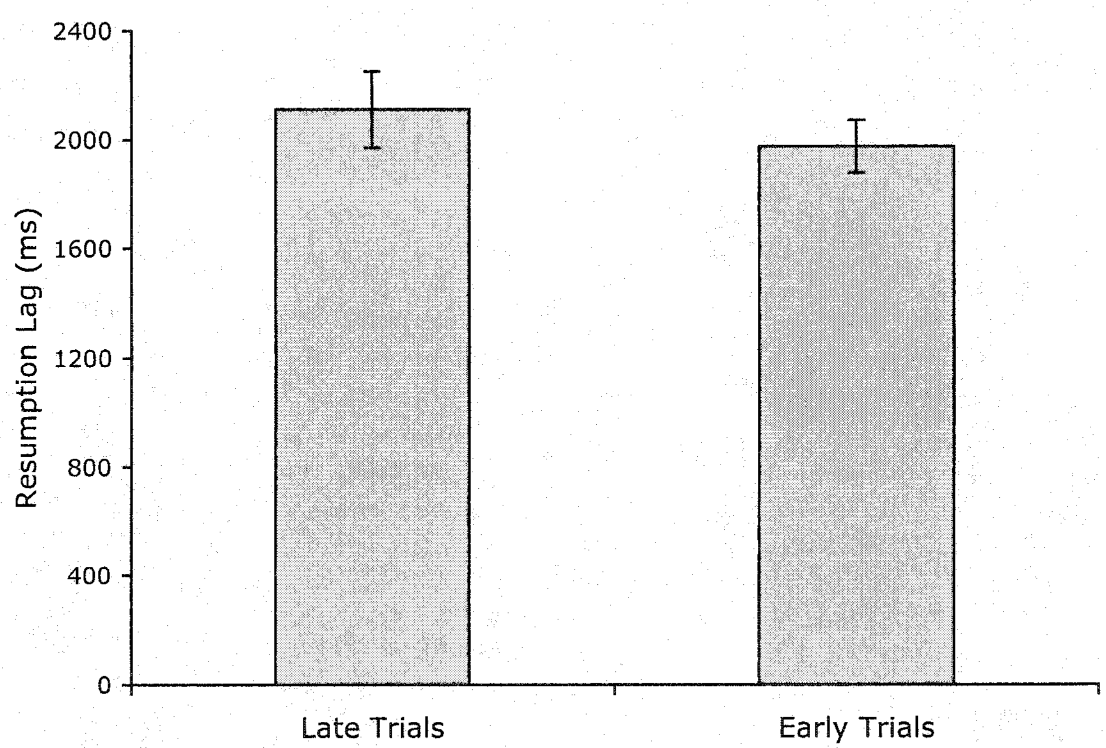

Figure 5. Resumption Lag Results for Early vs. Late Conditions.

As in the previous experiments, the inter-action intervals for clicks 2 through 4 were examined using tests of linear trend and paired comparison analyses. The inter-action interval pattern for both the early condition ($F(1, 13) = 10.85, p = .006, MSE = 25{,}193$) and the late condition ($F(1, 13) = 11.87, p = .004, MSE = 57{,}318$) showed a significant linear trend that clearly demonstrated the residual disruption effect (see Figure 6). The Activation Momentum explanation also predicted that the average post-resumption inter-action intervals should be faster for the late interruption condition. Contrary to this prediction, the results showed the opposite pattern; the early condition resulted in much faster inter-action interval times than the late condition, $F(1, 13) = 7.90$, $p = .015$, $MSE = 71{,}216$ (see Figure 6).

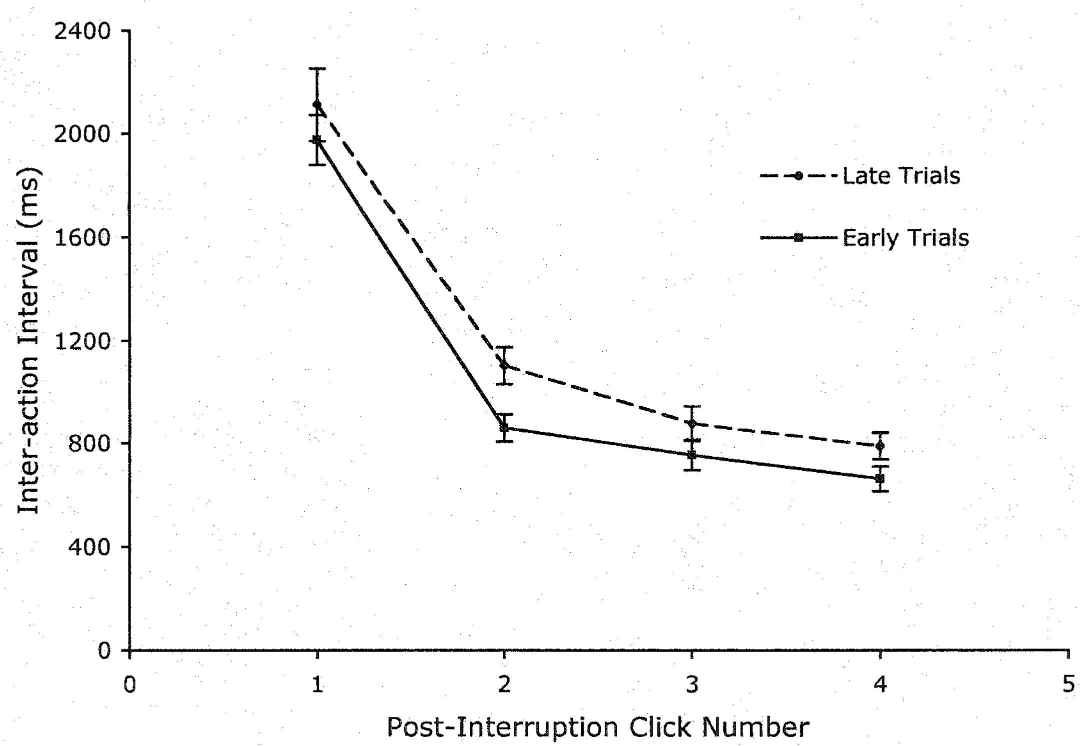

Figure 6. Inter-action Interval Results for Experiment 2.

The interaction between the early and late conditions was not significant, $F(2, 26) = 1.16, p = .329, MSE = 27{,}409$, nor was the interaction between the linear trends, $F(1, 13) = 1.39, p = .10, MSE = 32{,}877$. The similar slopes of the post-resumption inter-action interval patterns indicate that the residual disruption effect was equally present in both the early and late conditions.

The data do not support the Activation Momentum explanation for the residual disruption effect. It could be argued that the point of interruption effect demonstrated by Monk, Boehm-Davis, and Trafton (in press) and Monk, Boehm-Davis, and Trafton (2002) may have overshadowed a more subtle effect due to the build-up of activation predicted by Activation Momentum explanation. The studies looking at point of interruption showed that the more costly time to interrupt a task is during the middle of executing that task. It was comparatively less costly in terms of resumption time to interrupt people between subtasks (i.e., before starting a new subtask) or during a highly motor task like scrolling repetitively to a target. These findings corroborate the results from this experiment because the Activation Momentum explanation would predict that resumption lags should be longer at the beginning of a task compared to later in the task. Again, the opposite is true for both the interruption timing manipulation in the present experiment, and in the point of interruption manipulation in previous experiments. Because there was only one interruption in each trial in Experiment 3, there were insufficient data to test this hypothesis.

Taken together, it is clear that the Activation Momentum explanation for the post-resumption residual disruption effect not only fails to explain the effect, but also is essentially falsified by the results of this experiment. The next experiment will consider a completely different explanation that focused on the disruption of perceptual-based performance and the subsequent delay in resuming that performance level.

EXPERIMENT 3

The third experiment was designed to test the predictions of the Cognitive-Perceptual Shift explanation of the residual disruption effect that is based on the transition from memory-based performance to perceptual-based performance after an interruption. During skill acquisition people frequently achieve levels of task performance that require few (or fast) memory retrievals for each goal or interface action. This performance state can be characterized as perceptual-based performance because people rely more on task-relevant stimuli to prime their next actions rather than their memory of the task sequence. For example, after clicking the Start-hour button on the VCR, people typically had no difficulty remembering to then click on the Up or Down arrow button to adjust the setting. During the practice trials, the association between these buttons was strengthened to the degree that clicking the Start-hour button strongly primed the need to click the up or Down arrow to adjust the setting.

Memory-based performance is characterized less by perceptual cues and more by the need to retrieve next actions from memory, which is more costly for response times. In this case, the participant would not have been strongly primed to click the Up or Down arrow after clicking on start-hour. Instead, the participant would spend time retrieving the next action from memory, similar to asking him or herself, "Now what do I do?" The Cognitive-Perceptual Shift explanation argues that interruptions disrupt perceptual-based performance and cause people to revert temporarily to memory-based performance until they can re-transition to perceptual-based performance.

The perceptual- and memory-based performance levels can best be understood by considering the basic three-stage stimulus response model. First, people perceive the stimuli, then select a response, and finally execute this response (e.g., Pashler, 1998). For example, in the VCR task participants perceived that the target start-hour had been reached via scrolling the Up or Down arrow button. They then retrieved the next response from memory, which was to click Enter. Finally, they moved the mouse cursor to the Enter button and clicked it to execute that response. For the most part, response execution times are consistent (e.g., click times, mouse movement times, etc.) so the focus is on stimulus perception and response selection.

Response selection involves retrieving the appropriate response from memory. Memory retrievals can take more or less time, depending on the level of activation of the to-be-retrieved memory chunk (Anderson, Bothell, Byrne, & Lebiere, in press; Anderson & Lebiere, 1998). Retrieval times are also affected by the strength of the connections between the stimuli and the to-be-retrieved information. When the link between the stimulus and response is relatively weak, more retrieval time is required. Memory-based performance is characterized by the need to rely on time-consuming goal retrievals when the stimulus fails to prime a response.

Alternatively, when the link between the stimulus and response is strong, memory retrievals occur very quickly. In perceptual-based performance, people perform with minimal time between interface actions (i.e., goals) because they have strong associations between each serial goal in the hierarchy. Indeed, Frensch (1991) showed that people were faster when performing a sequence of operations when the operations were practiced in sequence compared to when they were practiced in random order (equivalent total practice). Again, after setting the start-hour setting to the target, the next action was to click the Enter button. The action of scrolling to the entry target was strongly associated with clicking the Enter button, as developed in the training trials. Memory retrieval for clicking Enter was nearly automatic because of this strong association.

Regarding the perceptual stage, Haider and Frensch (1996) argued that a source of speed-up in performance during skill acquisition is the reduction in processing task-irrelevant information. As people become more skilled in a task, they learn to ignore task-irrelevant information, thereby improving their efficiency. This theory has empirical support from two eye-tracking studies (Haider & Frensch, 1999; Lee & Anderson, 2001). It may be that people need to spend more time searching for relevant stimuli, and therefore process task-irrelevant information, in memory-based performance. Perceptual-based performance is more rapid because task-irrelevant information is ignored, as argued by Haider and Frensch.

The post-interruption inter-action interval patterns for the start-task condition in Experiment 1 suggest that people always begin a new task trial with greater reliance on memory, and then quickly transition to perceptual-based performance. The similar results for the interruption condition in Experiment 1 suggest that resuming a task after an interruption is very similar to starting a new task in terms of inter-action intervals. This implies that people temporarily revert to memory-based performance after an interruption until they can re-transition to perceptual-based performance. It is this transition period that produces the residual disruption effect. The return to memory-based performance may be due to decayed goal activation during the interruption period.

If indeed the cause of the residual disruption effect is the time to re-transition from memory-based performance to perceptual-based performance after an interruption, then interruptions that are short enough to minimize goal decay and interference should result in the elimination of the residual disruption effect. In addition, Sperling (1960) showed that visual information decays from sensory memory very rapidly. Therefore, previously perceived stimuli should still be active in sensory memory for interruptions of 1 second or less. The still active memory traces should allow participants to continue their task at the same performance level. In other words, because the brief interruption would be nothing more than a quick visual interruption, the perceptual-based task performance should be maintained across interruptions. The resumption lags should also be shorter for the shorter interruptions, as was found by Monk, Trafton, and Boehm-Davis (in preparation).

To provide an appropriate comparison condition, an uninterrupted condition was included. To show that people do in fact reach a stable inter-action interval time, four inter-action interval times were extracted from the uninterrupted condition at the corresponding times when the interruptions occurred in the other conditions (i.e., every 5 seconds). These data were then compared to the inter-action interval data in the interruption conditions. In the uninterrupted condition, it was expected that all four post-interruption inter-action intervals would be very similar, showing a relatively flat pattern.

As with any task, some level of learning was expected in the data. It is important to note that even though the Cognitive-Perceptual Shift explanation predicts no disruption to previously achieved performance levels, the resumption lags should still be longer than the first click in the uninterrupted condition by simple virtue of having to resume the task after an interruption.

Because there was no time for participants to work on an interruption task during the brief interruption conditions, the tracking task condition was not used in the longer interruption condition either. It has been shown that people are faster at resuming the VCR task when there is no interruption task versus the tracking task (Monk, Boehm-Davis, & Trafton, in press), but the post-resumption residual disruption effect should still be present as it was for the start-task control condition in Experiment 1.

Method

Participants. Twelve undergraduates from the George Mason University psychology subject pool participated in this study as a course requirement. Eleven women and one man participated and ranged in age from 18 to 27, with an average age of 20 years.

Materials. The VCR task was identical to that used in earlier experiments. The interruption periods in this experiment did not contain any task. During the interruptions, both sides of the screen went blank and the participant was required to wait until the VCR was displayed again before resuming the programming task.

Design. The experiment was a single factor within-subjects design with four levels of interruption duration. There were three interruption lengths (1/4 second, 1 second, and 5 seconds) and a no-interruption condition. In the 1/4-second condition, the interruption was hardly more than a flash of the VCR display off and then on again. In the 1-second condition, the flash was a little longer, but very brief nonetheless. The measures were the same as in the previous experiments.

Procedure. The VCR task training procedure was identical to that in the previous experiments. Participants were not given the tracking task practice because this experiment did not employ the tracking task interruptions. For the interruption practice trials, participants performed two 5-second interruption trials as in Experiment 1. For each trial, participants began with the VCR task and were interrupted every 5 seconds, creating a back-and-forth sequence between the VCR and interruption task in an interlaced fashion until the VCR program entry was completed. Participants completed 20 experimental trials, each with new show information to be programmed. Five trials were dedicated to each of the four conditions. Participants were instructed that some of the trials would not be interrupted, some would have very brief interruptions, and others would have longer interruptions. Trial order was randomized for each participant.

Results and Discussion

This experiment targeted the predictions of the Cognitive-Perceptual Shift explanation through the interruption duration manipulation. Therefore, the primary analysis was focused on the post-resumption inter-action interval (clicks 2 through 4) as in the previous experiments. Preliminary comparisons between the 1/4-second and 1-second conditions revealed that they were nearly identical for all of the dependent measures. Therefore, for analysis purposes these two conditions were combined into a "brief" interruption condition for comparison with the 5-second interruption condition and the uninterrupted condition.

The uninterrupted condition was analyzed by taking inter-action interval times for four clicks that matched closest to the point of interruption times in the interruption conditions. In other words, four inter-action interval measures were taken at every 5-second interval in the uninterrupted condition to provide an appropriate comparison for the post-resumption residual disruption effect. It was predicted that this condition would result in a fairly flat pattern because performance would be uninterrupted.

A repeated measures ANOVA on the post-resumption inter-action intervals with the uninterrupted, brief interruption, and 5-second interruption conditions showed that the main effect for condition was significant, $F(2, 22) = 7.47, p < .01, MSE = 5{,}495$. The uninterrupted condition resulted in the shortest inter-action intervals ($M = 621$ ms, $SD = 117$), followed by the 5-second interruption condition ($M = 664$ ms, $SD = 119$). The brief interruption condition had the longest mean inter-action intervals ($M = 687$ ms, $SD = 142$). Paired comparisons showed that the uninterrupted condition was significantly faster than either the brief or 5-second condition, which were not significantly different from each other. It was not surprising to see that the uninterrupted condition resulted in the fastest post-resumption inter-action intervals because there was no associated resumption cost. Further, there was no significant linear trend for the uninterrupted data, $F(1, 11) = 1.26$, $p = .29$, $MSE = 7{,}129$, indicating a statistically flat pattern.

The importance of the statistically flat pattern for the uninterrupted condition is underscored by the subtle slow-down in the pre-interruption analysis from Experiment 1. Whereas the pre-interruption results from Experiment 1 failed to show a stable inter-action interval level, the uninterrupted condition results from this experiment showed that such a stable performance level was possible in the VCR task. The stable inter-action interval pattern in the uninterrupted condition provided stronger evidence that the post-resumption performance trend does indeed reflect a residual disruption effect.

In contrast to the flat trend in the uninterrupted condition, the linear trends for the brief and 5-second interrupted conditions were both significant ($F(1, 11) = 19.43$, $p < .001$, $MSE = 13{,}182$ and $F(1, 11) = 19.77$, $p < .001$, $MSE = 7{,}095$, respectively). Paired comparisons showed that each click was significantly faster than the previous one for the brief condition. A similar pattern of data was found for the 5-second condition with the exception that the third and fourth clicks were not significantly different.

As is evident in Figure 7, the post-resumption inter-action interval patterns for the brief interruption and 5-second interruption conditions were very similar, $F(1, 11) = 1.22$, $p = .29$, $MSE = 7{,}631$. The interaction between these two linear trends was not significant, $F(1, 11) = 2.32$, $p = .16$, $MSE = 3.725$, showing that the two trends exhibited similar slopes. Recall that the Cognitive-Perceptual Shift explanation predicted that the brief interruption condition should be significantly flatter than the 5-second condition. However, this key prediction was not supported in these data.

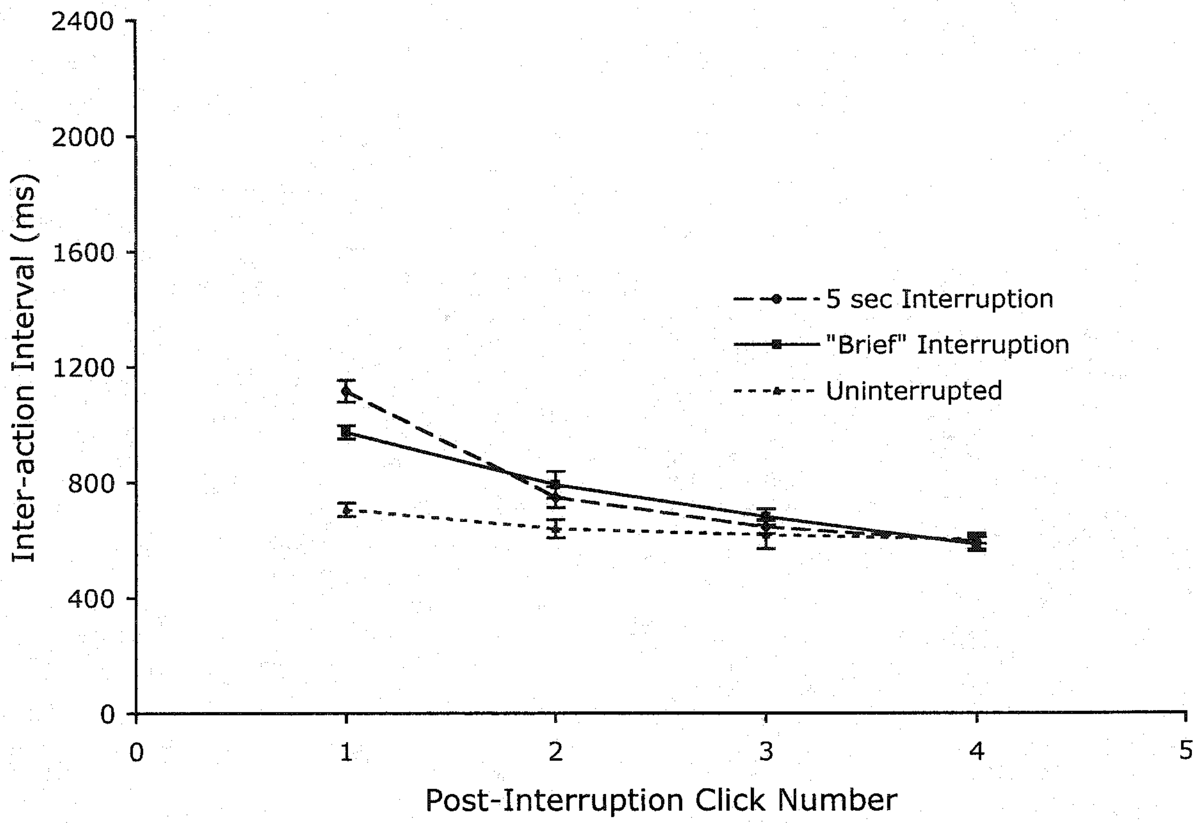

Figure 7. Inter-action Interval Results for Experiment 3.

The resumption lag data were also of interest because Monk, Trafton, and Boehm-Davis (under review) showed that resumption lag was sensitive to interruption duration. They found that longer interruptions resulted in longer resumption lags. The Cognitive-Perceptual Shift explanation predicted minimal disruption to pre-interruption performance levels for the brief interruption condition because of minimal goal and iconic memory decay. The Cognitive-Perceptual Shift explanation made no specific prediction regarding a small delay in resumption times. The resumption lag analysis showed that the main effect for condition was significant, $F(2, 22) = 74.25$, $p < .001$, $MSE = 6{,}992$. The uninterrupted condition had the fastest inter-action interval time (M = 706 ms, SD = 80), which was not surprising. Consistent with Monk, Trafton, and Boehm-Davis (in preparation), the brief condition (M = 974 ms, SD = 77) resulted in significantly faster resumption lags than the 5-second condition (M = 1115, SD = 129), $p < .001$. The fact that the resumption lags for the brief condition were significantly longer than the uninterrupted condition indicates that there is a price to be paid for resuming a task, regardless of the brevity of the interruption.

The results from this experiment showed that the residual disruption effect persisted even with the very brief interruptions that were predicted to preserve perceptual-based performance levels across interruptions. The Cognitive-Perceptual Shift explanation of the residual disruption effect was therefore unsupported by these data. After two failed attempts to explain the residual disruption effect, the fourth experiment produced empirical support for the Goal History explanation tested in Experiment 4.

EXPERIMENT 4

Recall that a goal's activation is partly determined by its retrieval history. Goals with more frequent or recent retrieval histories will have faster retrieval times. For example, entering the password when signing on to a computer network can be done with very little thought for most people who log in regularly. Because they frequently sign into the network, retrieving the password from memory requires very little effort. Likewise, in hierarchical tasks where goals or subgoals are often repeated (e.g., pushing the Enter button to conclude each data entry), these goals are retrieved faster than goals with less active goal histories. In general, this *repeat-benefit* will lower the average retrieval time for all the goals in a task when goals are repeated frequently over relatively short periods.

The repeat-benefit for goal retrieval is vulnerable to disruption because interruptions allow goal activation to decay to levels that require additional retrieval time. In other words, the retrieval time for a goal last accessed before an interruption will be slowed because that goal's activation level will have decayed during the interruption. The ACT-R memory decay function (Anderson & Lebiere, 1998), simplified by Altmann & Trafton (2002), determines a goal's activation by the number of times that it has been sampled (i.e., strengthened) and the time since it was first sampled (i.e., the goal's lifetime). A goal that is no longer the focus of attention will immediately begin to decay.

Therefore, goals that decayed during an interruption will diminish the repeat-benefit in hierarchical tasks.

Figure 8 shows how an interruption disrupts the goal repeat-benefit. In panel A, the second retrieval of goal A benefits from recently being the focus of attention (first retrieval of goal A). The third instance of goal A also benefits from the first and second retrievals. A similar pattern is seen for goal B. However, panel B shows a diminished benefit when an interruption is inserted into the goal sequence. Because of goal decay during the interruption, the second retrieval of goal A benefits from the first instance much less than when no interruption occurs between the two instances. Goal B also suffers from the diminished repeat-benefit because of the interruption. The beginning of a new goal history, and therefore a new repeat-benefit, is seen as the third instance of goal A benefits from the second instance because both occurred after the interruption.

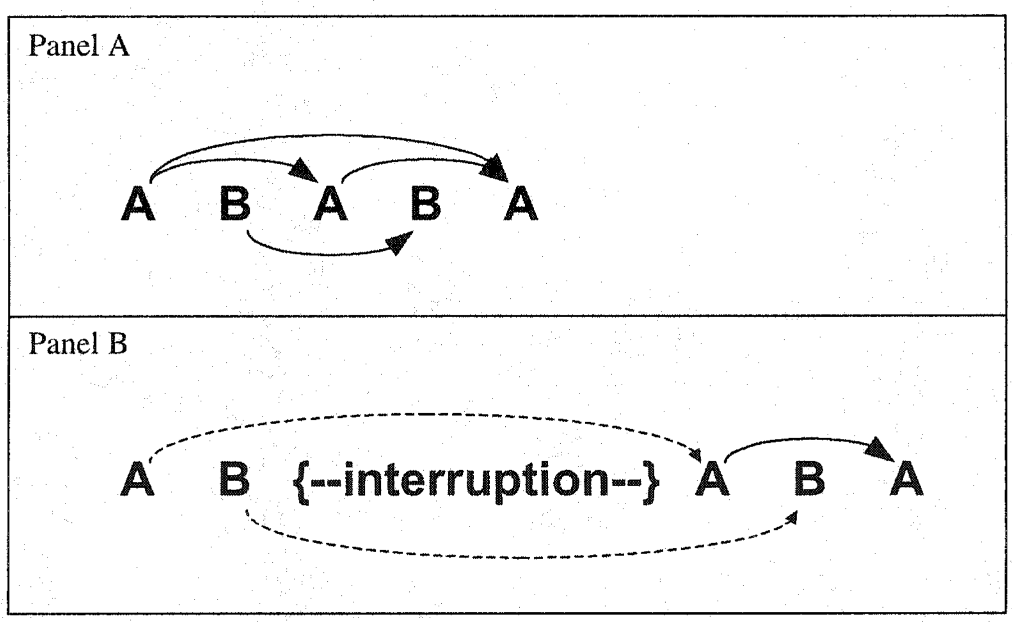

Figure 8. Repeat-Benefit Example for Goal History Explanation

It is the repeat-benefit that distinguishes the Goal History explanation from the Activation Momentum explanation. Both explanations argue that the residual disruption effect is due to higher levels of activation for future goals. However, the Activation Momentum explanation argues that activation levels are boosted due to associative priming through a mediating goal rather than due to the repeat-benefit of the Goal History explanation. In other words, the Activation Momentum explanation suggests that goal repetition is less important than the association between goals and subgoals, whereas the Goal History explanation argues that the residual disruption effect is due entirely to goal repetition.

As previously noted, the average retrieval time across all goals in a task is reduced because of repetition. An interruption inserts a period of goal decay into the hierarchical task sequence, and the result is much like having to restart the task from the beginning in terms of the repeat-benefit. Therefore, goals that immediately follow an interruption will benefit less from their history because of decay. Over time, as goal retrievals are once again repeated *after the interruption*, the repeat-benefit will return. The resumption of the repeat-benefit is a gradual process because goals are retrieved serially (Rohrer, Pashler, & Etchegaray, 1998). The Goal History explanation argues that the steady reduction in inter-action intervals that characterizes the residual disruption effect is the result of the resumption of the repeat-benefit as goals are once again repeated after an interruption.

The Goal History explanation also accounts for the presence of the effect for the task start-task condition in Experiment 1. Figure 3 shows nearly identical inter-action interval patterns for the post-interruption clicks when first starting a trial (start-task control condition) and when resuming the VCR task after an interruption. Because the goals at the beginning of a task had little activation history, they could not benefit from previously elevated activation levels as with repeated goals. Similar to the interruption scenario, the goal repeat-benefit was a gradual process as people progressed through a hierarchical task.

As a hierarchical task, the VCR programming task involved the repetition of many goals and subgoals throughout the task. For example, the Enter button was clicked after each show information entry (e.g., start-hour, day-of-week, etc.). If a goal was encoded and retrieved every time a button was pressed, then its activation level would have been incremented each time. More repetitions, or repetitions in close temporal proximity, would have resulted in faster retrievals. The repeat-benefit combined with greater opportunities for repeat clicks in click positions 2, 3 and 4, resulted in the post-resumption residual disruption effect. For example, if the Up button was the first click to resume the task after an interruption, and the Up button was then immediately clicked again twice more, the Up button's goal activation would have been boosted twice. By the third time the Up button was clicked, its activation level would have been higher and therefore its execution time would have been faster than a goal that had been repeated fewer times. Table 1 shows how goals in later click positions have greater likelihood of being repeated.

Table 1. Proportion of Repeated Goals Across Post-Interruption Click Number

Post-Interruption Click Number			
1	2	3	4
—	—	—	—
I	R	—	—
I	—	R	—
I	—	—	R
I	R	R	—
I	R	—	R
I	—	R	R
I	R	R	R
—	I	R	—
—	I	—	R
—	—	I	R
—	I	R	R
I	R	I'	R'
I	I'	R	R'
I	I'	R'	R
Total Repeats	5	8	10

I = initial goal retrieval
R = repeat of goal I
I' = second initial goal retrieval
R' = repeat of goal I'

If the Goal History explanation is correct, there should be two ways to eliminate the residual disruption effect. First, by interrupting the repeated execution of the same goal (e.g., repeated scrolling clicks), the repeat-benefit described by the Goal History explanation should be relatively equivalent for all inter-action intervals as the times approach asymptote. In other words, if the same single goal is repeatedly retrieved, the inter-action interval pattern should be flatter because that goal's activation level will reach levels where response times are limited only by motor control limits. Therefore, it was predicted that the post-resumption inter-action intervals for a condition where all post-interruption buttons were the same (repeat-same button condition) would be flat across the three post-resumption click positions.

Unfortunately, this prediction is not compelling because it relies more on motor control execution than memory retrievals. Upon resumption, all the participant must do is decide whether or not the target has been achieved and then either continue to repeatedly click the button or stop. Alternatively, a condition that involves no repeated button clicks (no-repeat button condition), and therefore no repeat-benefit, provides a more convincing test of the Goal History explanation's prediction. With no repeated clicks in the four-click series after each interruption the repeat-benefit should be minimized and therefore the residual disruption effect should be drastically reduced. This experiment used these two conditions to test the predictions of the Goal History explanation.

Because of the nature of the VCR task, it was only possible to reduce repeated clicks to a frequency of once every seven clicks. This reduced repeat-click level was sufficient for the purposes of this experiment because the focus was on eliminating the local repeat-benefit in the four button clicks immediately following an interruption (i.e., the post-resumption inter-action interval pattern). Because there were button repeats globally in the task, it was possible to have some lower level of benefit carryover across interruptions; however, it was believed that the 5-second interruption duration was sufficient to reduce this global benefit to a negligible level.

Method

Participants. Twelve undergraduates from the George Mason University psychology subject pool participated in this study as a course requirement. Eleven women and one man participated and ranged in age from 17 to 26, with an average age of 21 years.

Materials. The VCR and interruption tasks were identical to those used in Experiment 1.

Design. The experiment was a single factor within-subjects design with three levels of task condition: the repeat-control condition, the no-repeat condition, and the repeat-same condition. The repeat-control was the same as the interrupted conditions in Experiment 1 except that the interruptions occurred every 5 seconds instead of every 10 seconds. The control condition included the normal likelihood of repeated goals in the VCR task. The no-repeat condition consisted of VCR target shows that reduced repeat clicks on the same button to no more often than once every 7 clicks, thereby eliminating button repeats within any four-click sequence. This was accomplished by setting the target show information as a single increment (up or down) from the default setting. For example, the start-hour target was 5 when the default setting was 4; only one click on the up arrow was required to reach the target.

The repeat-same condition involved all repeated clicks. This was implemented by having participants repeatedly scroll the channel setting on the VCR to a channel number in the 90s, starting from channel 5. Participants had to click on the Up button for each increment; they were not able to click-and-hold until the target was reached. Participants were typically interrupted three or four times while scrolling to the target channel. The two experimental conditions were included in a single trial. Selections for the start-time, end-time, and day-of-week were made to ensure no repeat button presses. Changes to the channel number required repeated scrolling clicks totaling in the neighborhood of 80-90 clicks, creating the repeat-same condition. The interruptions that occurred while participants entered the start-time, end-time, and day-of-week were included as the no-repeat condition data, and the interruptions occurring during the channel scrolling were the repeat-same condition data. Participants performed the tracking task during the interruptions as they did in Experiments 1 and 2. The measures were the same as in the previous experiments.

Procedure. The procedure was similar to Experiment 1. Participants were first trained on the VCR task, then the tracking task, and finally with two interruption trials. The interruption duration was 5 seconds for the practice and experimental trials. Participants then performed 12 experimental trials with 6 trials in the repeat-control condition, and 6 trials in the experimental (no-repeat/repeat-same) condition. Participants were debriefed and dismissed.

Results and Discussion

For the post-resumption inter-action interval data (clicks 2 through 4), Figure 9 clearly shows a highly significant main effect for condition, $F(2, 22) = 480.65$, $p < .0001$, $MSE = 8{,}926$. The repeat-same button condition yielded the fastest average inter-action intervals ($M = 193$ ms, $SD = 27$), followed by the repeat-control condition ($M = 632$ ms, $SD = 105$). The no-repeat condition resulted in the longest average inter-action intervals ($M = 874$ ms, $SD = 121$). Paired comparisons showed significant differences between each of these conditions ($p < .001$ for all three pairs).

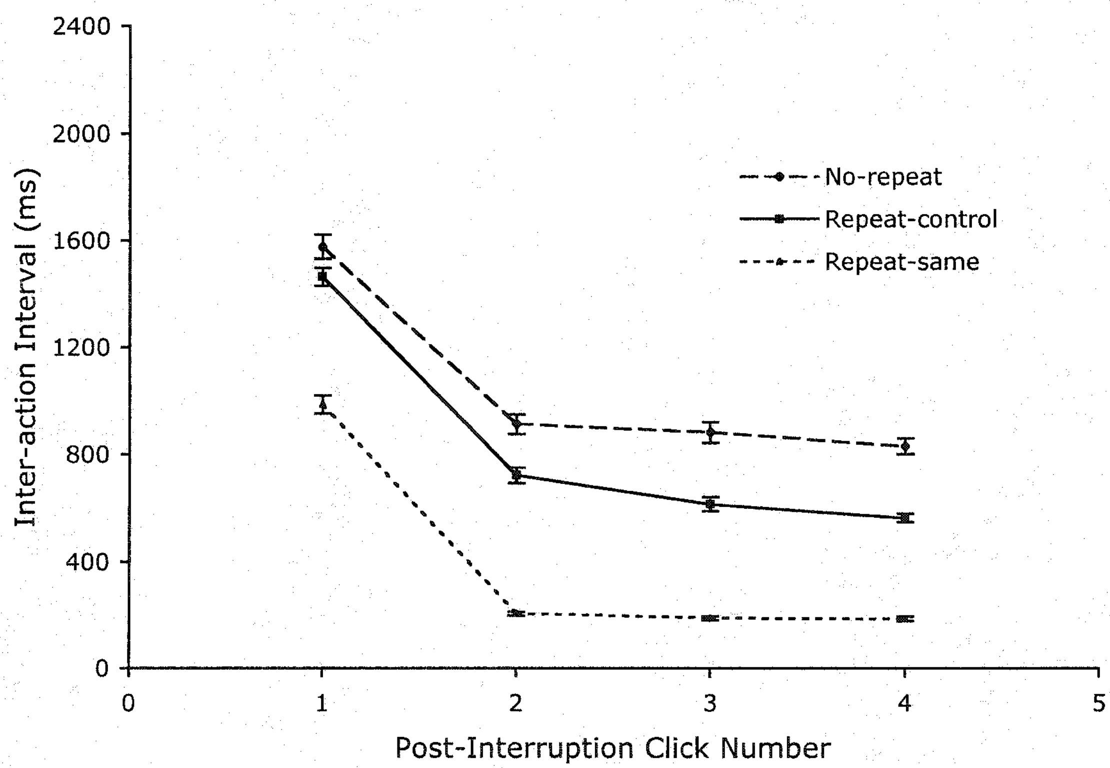

Figure 9. Inter-action Interval Results for Experiment 4.

As in previous experiments, the repeat-control condition showed the residual disruption effect in the form of a significant linear trend, $F(1, 11) = 29.96, p < .001, MSE = 5{,}111$. Each subsequent click was significantly faster than the previous click ($p < .001$ for all pairs). The Goal History explanation predicted that the no-repeat condition should not exhibit the speed-up effect; however, the linear trend was significant, $F(1, 11) = 28.69, p < .001, MSE = 1{,}412$. Although the trend was significant, the paired comparisons show that the difference between click 2 and 3 was not significant ($p = .223$) while the difference between clicks 3 and 4 was marginal ($p = .05$). These results suggest that the drop in inter-action interval for click 4 was the principal reason for the linear trend result.

Given that both the repeat-control and no-repeat conditions exhibited residual disruption effects, it was important to determine if these trends were equivalent, as they have been across conditions in previous experiments. The significant interaction between these trends revealed that the slopes were different, $F(1, 11) = 7.87, p < .05, MSE = 2{,}294$. Based on the paired comparisons reported above, it is clear that the residual disruption effect was flatter for the no-repeat condition. This finding supports the Goal History explanation's prediction, though not as strongly as predicted.

Additional support for the Goal History explanation comes from the repeat-same condition where despite the apparent flat pattern (see Figure 9), the linear trend was also significant, $F(1, 11) = 5.22, p < .05, MSE = 460$. Because the activation level for the repeated goal (button click) remained well above threshold due to repeated retrievals, it was predicted that the post-resumption inter-action interval pattern would be flat.

However, the presence of the small speed-up effect is not inconsistent with the Goal History explanation. Repeated boosts in activation should result in increasingly faster response times until a motor limitation is reached. Because the inter-action interval variance for the repeat-same condition was so low ($M = 193$ ms, $SD = 27$), participants were probably approaching this limit.

The Goal History explanation predicted that goals in the repeat-control condition had higher levels of activation compared to the no-repeat condition because they were suspended and resumed multiple times throughout the task. Therefore, the Goal History explanation predicted the fastest resumption lags for the repeat-same condition, followed by the repeat-control condition, and finally the no-repeat condition. The main effect for condition was significant, $F(2, 22) = 149.37$, $p < .001$, $MSE = 7{,}907$. Figure 10 shows the resumption lags for the no-repeat condition ($M = 1575$ ms, $SD = 155$), the repeat-control condition ($M = 1463$ ms, $SD = 115$), and the repeat-same condition ($M = 984$ ms, $SD = 115$). The repeat-same condition was significantly faster than the repeat-control condition ($p < .001$) and the no-repeat condition ($p < .001$), as predicted. The difference between the repeat-control condition and the no-repeat condition was marginally significant ($p < .05$).

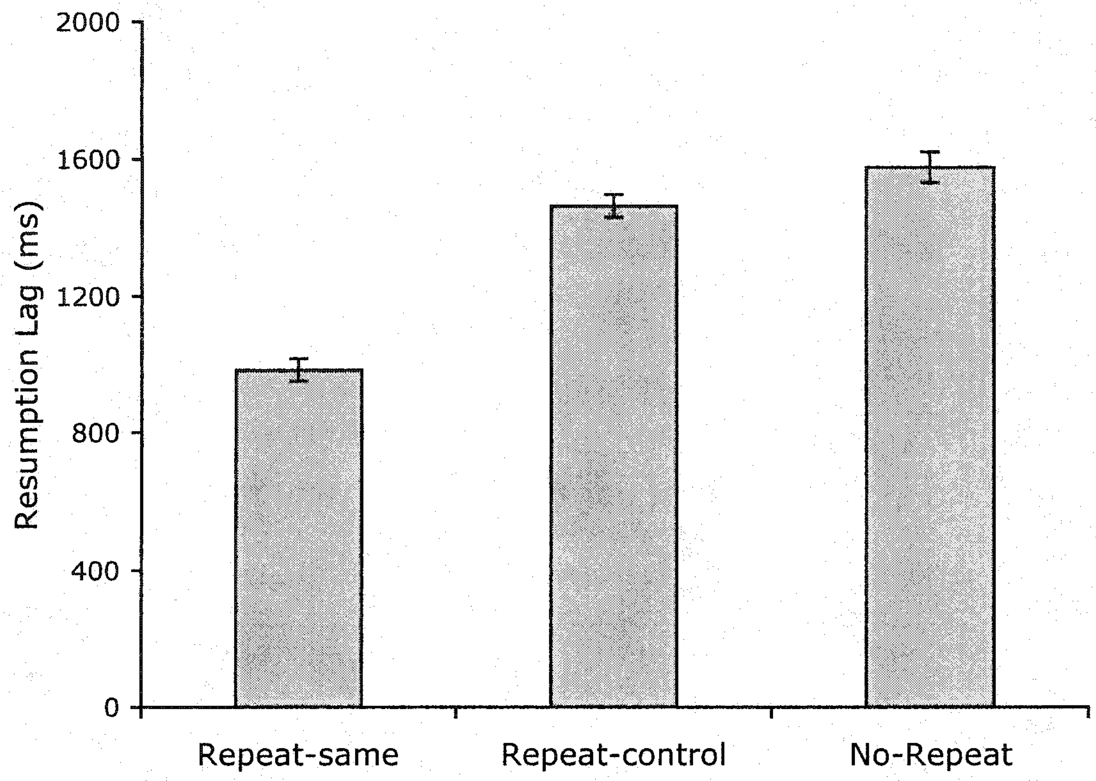

Figure 10. Resumption Lag Results for Experiment 4.

The results of Experiment 1 successfully demonstrated the presence of the residual disruption effect in interrupted task performance. Experiments 2 and 3 demonstrated that the Activation Momentum and Cognitive-Perceptual Shift explanations were unsupported. The results of Experiment 4 provided empirical support for the Goal History explanation of this effect. The no-repeat condition resulted in a flatter pattern of post-resumption inter-action intervals than the repeat-control condition. This outcome indicates that by eliminating the repeated goal retrievals in the four-click sequences, the residual disruption effect was greatly diminished. There may have been a global repeat-benefit that drove the linear trend in the no-repeat condition. Because the no-repeat condition was not completely without repeated goals, it is possible that these seldom repeated actions resulted in the subtle linear effect.

GENERAL DISCUSSION

In a series of experiments dedicated to testing three explanations of the residual disruption effect, the strongest evidence supported the Goal History explanation. Experiment 1 demonstrated the residual disruption effect for both the interruption and start-task control conditions. Experiment 2 examined the Activation Momentum explanation that predicted faster resumption lags and post-resumption inter-action intervals for interruptions occurring later in the task compared to interruptions occurring earlier in the task. This prediction was based on the assumption that goals later in the task should have had higher levels of activation due to spreading activation through the mediating task-level goal. Experiment 2 showed that not only were the later interruptions not associated with faster resumption and inter-action interval times, but that the opposite was true. The resumption lags were not reliably different, but the faster inter-action intervals were associated with the early interruption condition, thereby contradicting the predictions of the Activation Momentum explanation.

Experiment 3 tested the Cognitive-Perceptual Shift explanation that assumed perceptual-based performance levels could be maintained across very brief interruptions, and therefore participants would not revert to memory-based performance. By maintaining perceptual-based performance after an interruption, it was predicted that the residual disruption effect would be eliminated. However, the results showed that even for very brief interruptions, the residual disruption effect was present. This result provides compelling evidence against the Cognitive-Perceptual Shift explanation because the residual disruption effect was present under conditions when the explanation predicted it would be eliminated.

The results of Experiments 4 supported the predictions of the Goal History explanation. When repeated goals were eliminated from the post-interruption four click sequences, the residual disruption effect was greatly reduced. Similarly, the effect was minimized when all of the post-interruption goals were the same. These results provided support for the Goal History explanation; however, there may be yet another explanation that warrants consideration.

Might the residual disruption effect simply be due to interference from the interruption task on the primary task upon resumption? In other words, the participants shifted their attention to the tracking task during the interruptions, and were then forced to switch their attention back to the VCR task. The memory traces for the tracking task would have then interfered with the resumption of the suspended VCR task goals. The initial interference would have been the strongest, creating the resumption lag, but the interference would likely have persisted beyond the initial click (depending on the length of the resumption lag). The speed-up effect that characterized the residual disruption effect would reflect the decay of that interference as participants resumed the primary task.

The results from Experiment 3 provided an excellent opportunity to test the interference hypothesis. Because this condition did not contain a task during the interruptions, there was no source of interference to produce the residual disruption effect. The interference hypothesis predicts that without a source of interference during the interruption, the resumption of the primary task should primarily be affected by goal decay. The 5-second interruption condition in Experiment 3 contained no interruption and yet still showed both a resumption lag and the residual disruption effect. This indicated that the residual disruption effect was unaffected by the presence (e.g., Experiment 1, 2, and 4) or absence (e.g., Experiment 3) of a task during the interruption. Given the evidence from all four experiments, the Goal History explanation for the residual disruption effect was the only hypothesis to find empirical support.

The success of the Goal History explanation provides additional support for the goal-activation model (Altmann & Trafton, 2002) as a theoretical framework for the study of interruptions. Several studies have already demonstrated strong empirical support for the goal-activation model's predictions of post-interruption task resumption. Monk, Boehm-Davis, and Trafton (in press) and Monk, Boehm-Davis, and Trafton (2002) showed that resumption times can depend on where in the primary task the interruptions occur. Specifically, resumption times were fastest when people were interrupted between sub-tasks and during a repetitive operation like scrolling. Trafton et al. (2003) showed that resumption times were reduced when people prospectively rehearsed their goals during the interruption lag. Hodgetts and Jones (2003) showed similar results for the benefits of the interruption lag on resumption times. The present study adds to this catalog of support for the goal-activation model as it has provided the most compelling explanation for the residual disruption effect. To further demonstrate the goal-activation model's robustness as a theory of interrupted task performance, the multiple unexpected effects discovered in this series of experiments will be discussed for their consistency with the model.

The results from Experiment 1 showed the same residual disruption effect after an interruption as when a task was started from the beginning, although the post-resumption inter-action intervals were slightly, but reliably, faster than the post-start inter-action intervals. The goal-activation model can account for this effect because the goals at the start of a new task would not yet have much history. If the residual disruption effect were explained by the gradual process of task goals benefiting from higher activation because they were recently (or frequently) the focus of attention, then the effect would be expected at the beginning of the task as well. When starting a new task, the same delay in achieving the faster inter-action intervals would result because it takes a few clicks before goals can be repeated. Therefore, interruptions result in the same cost associated with task start-up—where it takes time before goal retrievals can benefit from having recently been the focus of attention.

The goal-activation model can account for the residual disruption effect when starting a new task, but how well can it account for the faster inter-action interval times associated with the interruption condition? Because the various goals in the interruption condition were repeated several times throughout a given trial, the activation levels for these goals were likely higher on average, leading to the slightly faster inter-action intervals for the interruption condition. The goals in the start-task control condition had no history and therefore could not benefit from elevated activation levels of goals previously the focus of attention.

The results of Experiment 2 showed that contrary to the predictions of the Activation Momentum hypothesis, interruptions occurring later in the task did not result in reliably faster resumption lags. In addition, the post-resumption inter-action intervals were significantly longer for the later interruptions, contrary to the predicted outcome (no difference in slope). How might the goal-activation model explanation account for this finding? Much like the explanation for the results of Experiment 1, inter-action intervals should have been faster when there was an activation benefit from repeated goals. However, the opposite was true in Experiment 2; the results showed that interruptions occurring early in the task had faster inter-action intervals. Although it is not specific to the goal-activation model, one possible explanation is that participants experienced within-trial fatigue as they progressed through the VCR programming task. The VCR task consists of several subtasks that involve a similar sequence of clicks (e.g., entering the start-hour is very similar to entering the end-hour). As participants advanced through the task, they may have begun to slow down as a matter of fatigue or boredom. The early condition would not have been affected because the fatigue or boredom would not have set in during the early part of the task.

This argument seems to contradict the argument for the results of Experiment 1 (that start-up inter-action intervals were slower than those later in the task); however, it should be noted that the start-task control condition in Experiment 1 consisted of the first four goals (i.e., clicks) at the beginning of a new trial. Because the interruption condition in Experiment 1 consisted of multiple interruptions occurring every 10 seconds, the condition is similar to the early interruption condition in Experiment 2 rather than the late interruption condition. However, if the fatigue explanation is correct, there may be evidence from another study by Monk (2004) that compared frequent and infrequent interruptions.

Monk (2004) found that frequent interruptions (i.e., every 10 seconds) resulted in significantly faster resumption lags and post-resumption inter-action intervals than infrequent interruptions (i.e., every 30 seconds). The repeated suspension and resumption of the goals in the frequent condition may have resulted in a more aggressive goal maintenance (i.e., rehearsal) strategy than in the infrequent condition, resulting in faster retrieval times for the frequent condition. In addition, it is likely that the more aggressive goal maintenance strategy would have reduced any fatigue experienced in the infrequent condition. Although there is good reason to accept the fatigue explanation of the Experiment 2 results, further research is required to answer this question conclusively.

Experiment 3 tested the claim that the residual disruption effect was due to a temporary relapse to memory-based performance after an interruption. However, the result showed that even for interruptions as short as 1/4 second in duration, the residual disruptive effect was present. It was argued that the perceptual-based performance should have been maintained over such a short interruption. This prediction was not supported. How does the Goal History model account for this effect? It could be that the experimental paradigm controlled for repeated goal retrievals within any given 4-click sequence. However, in the 1/4-second and 1-second interruption conditions there could easily be carryover repeat-benefit between post-interruption click sequences. For example, if the sequence for a couple of interruptions was: Interruption A, Column 1, Start-Hour, Up, Enter, Interruption B, Column 1, Column 2, Start-10, Up, it is evident that goals repeating across interruption sequences could have resulted in faster retrievals. If a very brief interruption were inserted in Figure 7, panel B, the post-interruption goals would still benefit from the activation levels of the pre-interruption goals.

Altmann and Trafton's (2002) memory for goals framework can reasonably account for the various effects encountered in the present series of experiments. Further research should be conducted to truly test the model's accounts of these effects. For example, another experiment could be conducted to test the hypothesized cross-interruption carry-over repeat-benefit that may account for the subtle speed-up in the no-repeat condition in Experiment 4. This experiment could also serve to further explore the results from Experiment 3 that showed that even for the briefest interruptions, there is a penalty to be paid when resuming the primary task.

The results of the current study also have an impact on the Activation Momentum explanation, which was contradicted by the results of Experiment 2. These results combine with the results of Monk, Boehm-Davis, and Trafton (in press), that showed that task boundaries are a strong determinant of resumption times, to make a compelling argument against the role of spreading activation through a mediating task-level goal in the residual disruption effect. The task-level goal model is very similar to the notion of a goal-stack, which has been abandoned by the ACT-R framework (Anderson, Bothell, Byrne, & Lebiere, in press). The results of this experiment do not argue against the role of spreading activation in hierarchical task performance in general, just its role in the residual disruption effect.

This series of studies contributes several important findings to the literature on interrupted task performance. First, a new effect was demonstrated repeatedly across multiple experiments (in fact, the effect was present in all four experiments). This effect, termed here the residual disruption effect, clearly shows that resuming a task after an interruption is not only delayed in the initial response, but also in the subsequent responses. Second, the data supported a theoretical explanation of these effects, the memory for goals framework (Altmann & Trafton, 2002). Previous interruptions research has focused mostly on identifying the disruptive characteristics of interruptions; however, they often lacked a solid theoretical basis for their predictions. The goal-activation model is the first such framework that provides a well specified theory for what makes interruption recovery, which is ultimately the most relevant measure of the impact of interruptions, quick and successful. Future interruptions researchers should seek to base their predictions on the goal-activation model, or some other detailed theory, rather than simply testing for interesting outcomes.

As with any study, the present experiments have some limitations that should be acknowledged. First, although the present study provided evidence in support of the Goal History explanation for the residual disruption effect, more research is required to fully distinguish this explanation from others, and to test for these effects in a different hierarchical task. In addition, the results of the present study are partly limited by the fact that the interruptions used in this paradigm were exogenously controlled, which is a condition different than most interruptions that people encounter. Typically, people can determine when to engage the interrupting task. For example, they can accept or decline a new instant message. McFarlane (2002) showed that the immediate interruption scenario used in the VCR interruption paradigm produces worse performance than when people can negotiate when to be interrupted. It would be interesting to test for the same types of effects when people are able to plan for interruptions. Indeed, the goal-activation model (Altmann & Trafton, 2002) makes predictions about the use of the time before an interruption (i.e., interruption lag) for planning. Trafton et al. (2003) showed that people spend time during the interruption lag rehearsing for their post-interruption goal-action. If people tend to only rehearse the to-be-resumed goal, and not the subsequent goals, then the residual disruption effect should persist even with interruption lag rehearsal. If people were to rehearse several subsequent goals in addition to the to-be-retrieved goal, then interruption lag rehearsal may diminish the residual disruption effect.

Another limitation of this study is that it used an interruption task that was relatively low in cognitive demand. People were likely able to spend time rehearsing their suspended goals during the pursuit-tracking task. Monk, Trafton, and Boehm-Davis (in preparation) showed that the resumption lag effects were even more extreme when a highly demanding cognitive task was used during the interruption compared to pursuit-tracking task used in this study. Overall, the impact of the relatively low demand interruption task should not have had a substantial impact on the residual disruption effect because the goal history is restarted after the interruption regardless of rehearsal. However, it could be that a more demanding interruption task would produce greater interference for task resumption as a whole. More research is required to answer this question in detail.

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APPENDIX A

PILOT EXPERIMENT

The purpose of this pilot study was to determine if there was any residual effect of interruptions beyond the resumption lag. An interruption condition similar to that used in Monk, Boehm-Davis, and Trafton (in preparation) was used along with a control condition where participants performed a series of abbreviated trials to capture the inter-action intervals after starting a new task trial.

Method

Participants. Ten undergraduates from the George Mason University psychology subject pool participated in this study as a course requirement.

Materials. The primary task was to program a VCR using a simulated VCR built in Macintosh Common Lisp. The VCR interface, originally designed for experimental use (Gray, 2000; Gray & Fu, 2001), was not based on a commercially available VCR. The interruption task was a pursuit-tracking task that required subjects to track a moving target with the computer mouse. The VCR and interruption tasks were presented side-by-side on a Macintosh G4 computer with a 17-inch VGA monitor. The VCR task was on the left side of the monitor and the tracking task was on the right side. Both tasks required only the computer mouse, and only one of the tasks was visible at a time.

VCR task. Programming a show consisted of four tasks: entering the show's start-time, end-time, day-of-week, and channel number. Two of these four tasks were broken down further into subtasks. There were three subtasks for the start-time (start-hour, start-

10min, and start-min) and three for the end-time (end-hour, end-10min, and end-min). The day-of-week and channel tasks contained no subtasks and therefore were considered to be equivalent to the subtask level rather than the task level. A detailed task analysis is available in Appendix B.

To better understand the steps involved in carrying out these subtasks, a description of entering the start-time was presented. To enter the start-time, the participant first clicked the Column button above the hour buttons (leftmost square button). This signified the beginning of the start-hour subtask. The participant then clicked the Start-hour button, and clicked on the Up or Down arrow multiple times until the displayed hour number reached the target hour. Next, the participant clicked on the Enter button to save the start-hour setting. Finally, to end this subtask, the participant clicked the Column button again (to "deselect" it) before moving on to the next subtask. Table 1 shows the pairing of the start-hour subtask operations with their respective subtask classifications. These subtask stages corresponded to the point of interruption manipulation.

The participant was required to repeat the same steps for the start-10 minute and start-minute settings to complete the start-time entry. The same process was completed for the end-time, day-of-week, and channel number entries, respectively. The VCR display was blank when no setting was selected. The participants had access to target show information (the show name, start-time, end-time, day of week, and channel number) at all times as the information was posted to the right of the monitor on a 3x5 index card.

Interruption task. The interruption consisted of a pursuit-tracking task. The tracking task required the participant to track an airplane (target) moving around the right half of the screen in a random pattern.

Design. The experiment was a single factor repeated measures design with two conditions: interrupted trials and start-up control trials. The primary dependent measure was the inter-action interval, which was defined as the time elapsed between the mouse clicks in the interface. The time between the offset of the interruption and the first mouse-click on a VCR button was the resumption lag measure. The inter-action intervals were measured for the first four clicks after each interruption or new trial start. The post-resumption inter-action interval pattern consisted of clicks 2 through 4 after an interruption (the first click defines the resumption lag). Each participant completed five interrupted and five control trials. Each control trial consisted of five blocks of eight shorter trials where the participant began the VCR programming task at a different point in the task and programmed only one of the eight subtask entries (e.g., start-hour) per mini-trial. Participants alternated between interrupted and control trials.

Procedure. Each participant was tested individually. The sessions, which lasted approximately one hour, began with the experimenter explaining the VCR task through a demonstration. The participants were then given two practice trials with the VCR task without interruption. After completing the practice with the VCR task, the participants were given two 60-second practice trials with the tracking task. The participants were then introduced to the interruption condition, where they alternated performing the VCR and interruption tasks. The participants were told that the cursor position for each respective task would be saved and reset upon each switch so that dragging the mouse back and forth between the two sides would be unnecessary. Resetting the cursor position with each switch to the VCR task eliminated problems with carry-over cursor movements from the tracking task. The two tasks were essentially paused when not active. After the two practice interruption trials, the participants completed a practice session with the control mini-trials before completing the experimental trials, each with new show information to be programmed. For each trial, participants began by programming the VCR. Interruptions occurred every 10 seconds and lasted for 5 seconds, creating a back-and-forth sequence between the VCR and interruption task in an interlaced fashion until the VCR program entry was completed. After completing the 10 experimental trials, the participants were debriefed and dismissed.

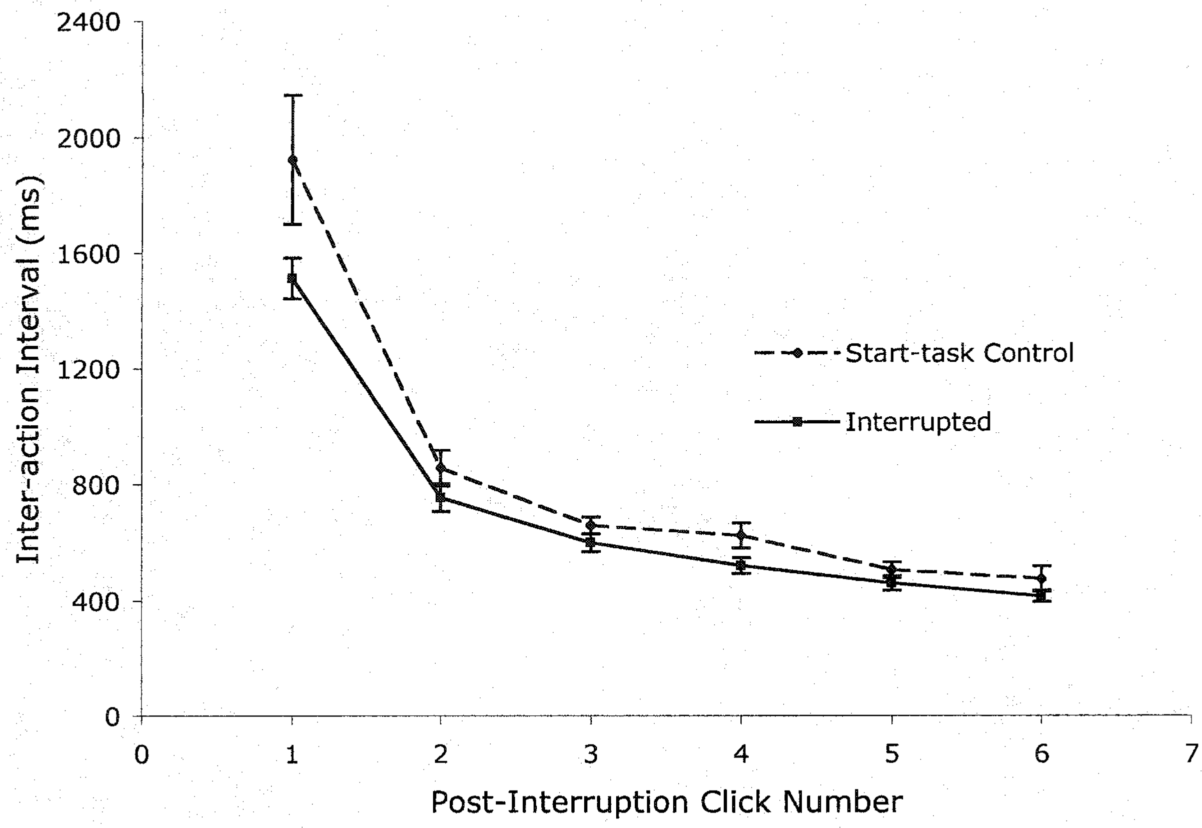
Results and Discussion

The analyses were restricted to address the specific goal of identifying the presence of a significant linear trend (speed-up) in the post-resumption inter-action interval pattern, thereby demonstrating the residual disruption effect. The figure shows the mean inter-action interval patterns for the control and interruption conditions. The main effect for post-resumption inter-action intervals (clicks 2 through 6) was indeed significant, $F(4, 36) = 47.38$, $p < .0001$, $MSE = 8{,}533$. All paired comparisons between the six points were significant ($p < .001$) except between clicks 4 and 5, showing that the inter-action intervals were for the most part faster with each successive click. These results demonstrate that the residual disruption effect was strongly present in the data.

To test the prediction that the mean resumption lag for the interrupted condition would be faster than the mean start-up lag in the control condition, the two lags were compared. The mean resumption lag for the interrupted condition (*M* = 1513 ms, *SD* = 225) was significantly shorter than the control start-up lag (*M* =1922 ms, *SD* = 703), $F(1, 9) = 5.099$, $p = .05$, *MSE* = 163,457.

The inter-action intervals were shorter for when the participants were interrupted compared to when they started a new trial (control condition), $F(1, 9) = 14.32$, $p < .01$, *MSE* = 9,611. The inter-action intervals continued to get faster with each successive click in both the interruption condition, $F(1, 9) = 42.90$, $p < .001$, *MSE* = 15,688, and control condition, $F(1, 9) = 86.62$, $p < .001$, *MSE* = 9.680. However, the interaction between the two slopes was not significant, $F(1, 9) = 1.07$, indicating that the residual disruption effect shared a similar slope regardless of condition.

This pilot study demonstrated that there was a residual disruption effect beyond the resumption lag for both interrupted and control trials. However, the slope of the effect was equivalent for both conditions, indicating that the inter-action intervals can be manipulated to be shorter or longer, but the trend of the residual disruption effect is more resilient.

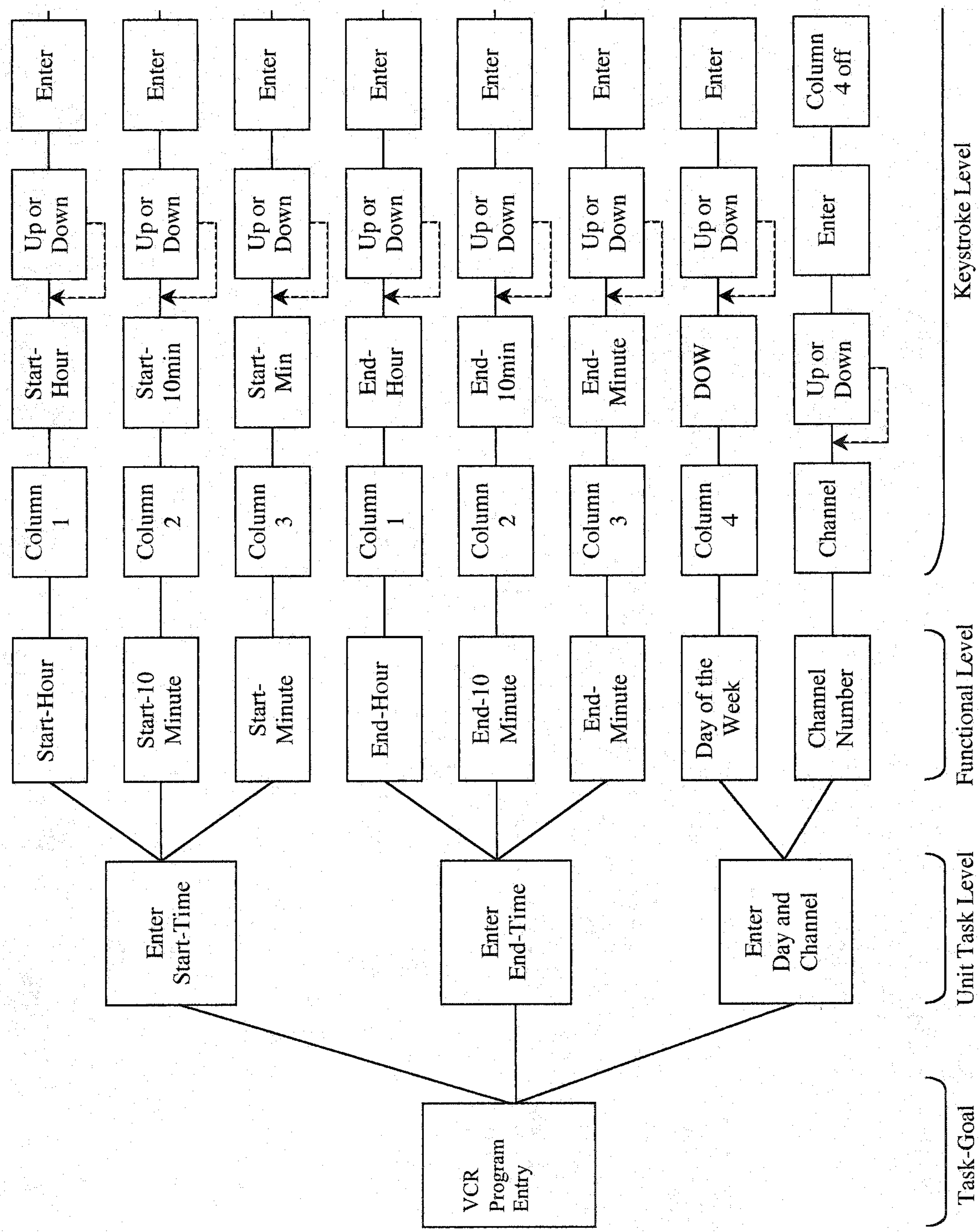


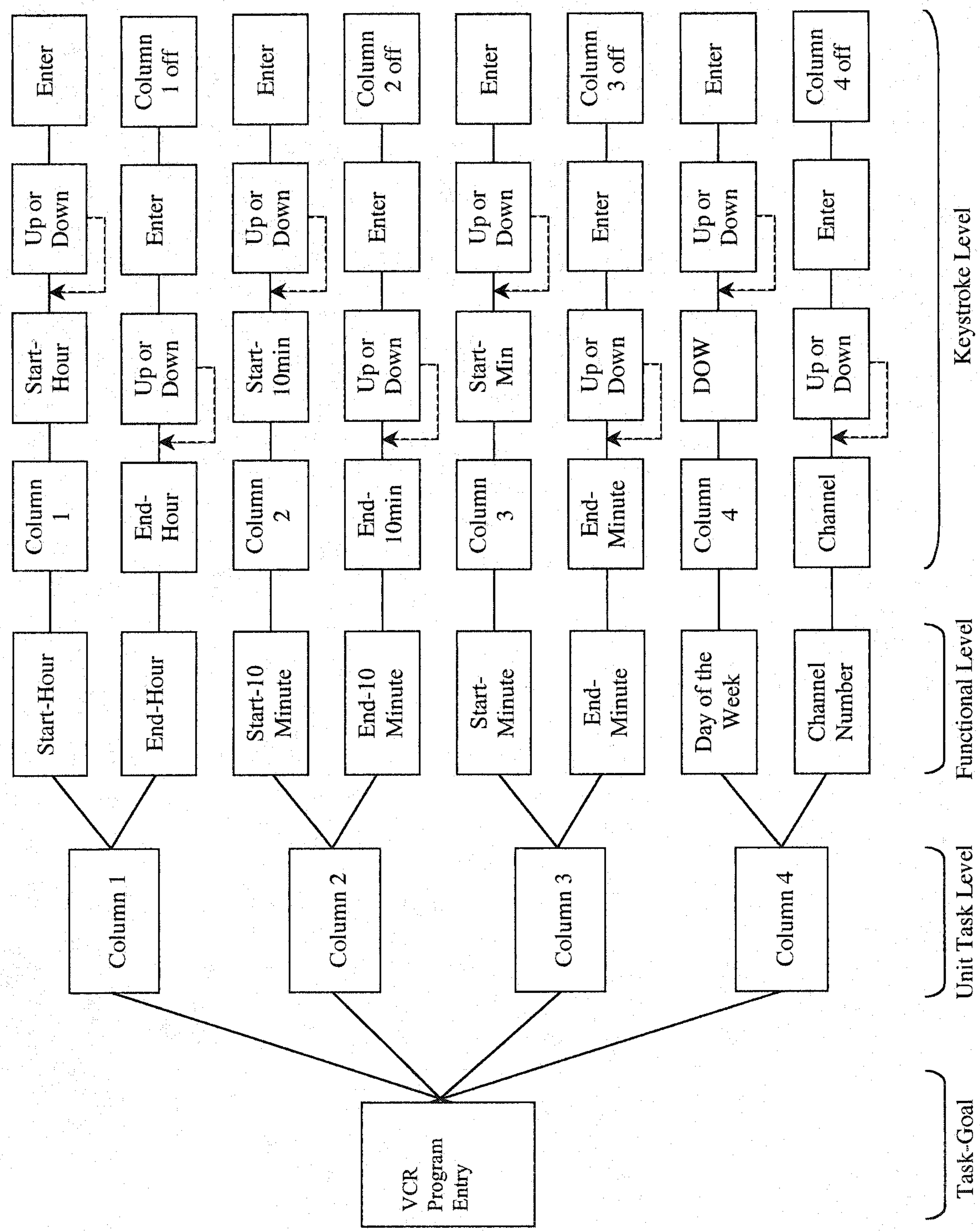
Appendix A Figure. Inter-action Intervals for Interrupted and Control Conditions

APPENDIX B

VCR TASK ANALYSIS

The VCR task was originally designed for experimental use (Gray, 2000; Gray & Fu, 2001) and was not based on a commercially available VCR. The two following figures illustrate the decompositional task analysis of the VCR task and represent the two general strategies for programming the VCR. This unit-task analysis was based on Card, Moran, and Newell's (1983) method of decomposing tasks into their keystroke level components. Although shifts in visual attention can be depicted in these types of task analyses (e.g., Lee & Anderson, 2000), only the keystrokes (mouse clicks) are portrayed in this analysis. The first figure depicts the "row strategy" for programming the VCR, which is decomposed into three unit tasks: (a) entering the start-time, (b) entering the end-time, (c) entering the day-of-week and channel number. Each of these unit tasks is then further decomposed into several function task levels. For example, to set the start-time the operator must enter the start-hour, the start-10-minute, and the start-minute. Each of these functional level goals in turn has several keystroke level goals that include shifts of attention, mouse movements, button clicks, and goal confirmations. The second figure depicts the same decomposition for the "column strategy" that was a more efficient strategy (i.e., fewer button clicks).


VCR Program Entry
Enter Start-Time
Enter End-Time
Enter Day and Channel
Start-Hour
Start-10 Minute
Start-Minute
End-Hour
End-10 Minute
End-Minute
Day of the Week
Channel Number
Column 1
Column 2
Column 3
Column 1
Column 2
Column 3
Column 4
Channel
Start-Hour
Start-10min
Start-Min
End-Hour
End-10min
End-Minute
DOW
Up or Down
Up or Down
Enter
Enter
Column 4 off
Task-Goal
Unit Task Level
Functional Level
Keystroke Level


VCR Program Entry
Column 1
Column 2
Column 3
Column 4
Start-Hour
End-Hour
Start-10 Minute
End-10 Minute
Start-Minute
End-Minute
Day of the Week
Channel Number
Column 1
Start-Hour
Up or Down
Enter
End-Hour
Up or Down
Enter
Column 1 off
Column 2
Start-10min
Up or Down
Enter
End-10min
Up or Down
Enter
Column 2 off
Column 3
Start-Min
Up or Down
Enter
End-Minute
Up or Down
Enter
Column 3 off
Column 4
DOW
Up or Down
Enter
Channel
Up or Down
Enter
Column 4 off
Task-Goal
Unit Task Level
Functional Level
Keystroke Level

CURRICULUM VITAE

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