EXAMINING THE ROLE OF SPATIAL MEMORY IN INTERRUPTIONS

by

William D. Miller, Jr.
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of
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Dedication

This work is dedicated to my parents, Linda and Bill, and my sister, Christina. Thank you for all your support, for always believing in me, and for helping me achieve my greatest goal.

Acknowledgments

I would like to thank the many people who influenced my growth and development during my academic career, and who helped me in completing this work. To Ryan McKendrick, thank you for your support, as both my friend and as a colleague who assisted me for countless hours throughout this process. To Bridget Lewis, Devon Kelley, and Nicholas and Angela Zapadka, thank you for your unwavering generosity, hospitality, and support. To Drs. Susan Davis and Justin Ericson, thank you for everything you taught me and for starting me on this path. To Justin Estepp, thank you for the constant mentorship and support through the years, and for always making time for me. To Nohelia Argote, Roberto Azanon, Skylar Kissam, Ammal Mahmood, Justine-Louise Manning, Arzo Raoufi, Mariam Talib, and Dennis Trammel, thank you all for your work in assisting me with data collection. I hope that each of you find success in your future academic endeavors. To my committee members, Drs. James Thompson and Matt Peterson, thank you for your insight and assistance with me completing this work.

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Abstract

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There has been little work investigating the role that the location of the primary task in the visual field plays following an interruption. The goal of this paper is to investigate the role that location plays in successfully resuming from an interruption and examine whether a well-known model of interruptions, Memory for Goals, should be revised to account for primary task location. The data suggest that changing the location of the primary task following an interruption can negatively impact resumption performance, but the effect is not consistent. We also show that there is little evidence that participants show anticipatory eye-movements towards the task between when the interruption ends and before the primary task resumes. Finally, we show that interruption performance does not improve when participants can anticipate where the primary task will resume following an interruption. These results suggest that there is no need to add an additional component to the Memory for Goals model that involves the primary task

location, and that participants are resilient to changes in primary task location following an interruption.

Introduction

If you look at the operating system (OS) on your phone or computer today, you will almost certainly have an entire section dedicated to notifications, where users can configure exactly what applications they want to be notified by and the means by which these notifications occur. Companies are even introducing digital assistants that plug into your calendar, managing notifications by reading your schedule and understanding when you are or are not busy. “Notifications” however, is just another way to describe interruptions, an area of interest that has continued to grow in software development and human-computer interaction communities in the last 15 years (Cutrell, Czerwinski, & Horvitz, 2001).

The effects of interruptions, brought about by cell phones, computers, or your officemates or roommates have been well-documented over the years. There is little argument that interruptions on the whole, are disruptive (Boehm-Davis & Remington, 2009), contribute to errors, anxiety, and frustration (Bailey & Konstan, 2006), suggesting that systems’ designers need to take into account the cognitive costs of interruptions when designing systems (Eyrolle & Cellier, 2000; McFarlane & Latorella, 2002). In spite of all the research documenting the impact of interruptions, the exact mechanisms involved in the recovery from interruptions are still not completely understood.

Three theories that attempt to explain these mechanisms using empirical support, Long-Term Working Memory, Memory for Goals, and Threaded Cognition, present strong cases. However, none of these theories adequately address the exact role that memory for spatial location plays in resumption from interruptions, despite the recognition that at least some memory for spatial location is used during resumption (Ratwani & Trafton, 2008). The purpose of this research proposal is to build off the initial investigations of the role of this particular form of memory in order to gain a more complete understanding of exactly how it contributes to one's ability to cope with interruptions.

Long-Term Working Memory

As a theory of interrupted task performance, Long-Term Working Memory is based on a memory store where information can be stored with associated cues, and memories accessed through an associated knowledge base (Ericsson & Kintsch, 1995). A key aspect of LTWM is its protection against decay through some type of efficient encoding framework, specific to a certain area of expertise or skill. For example, Hatano & Osawa (1983), observed that individuals who were able to expertly perform mental arithmetic using a mental representation of an abacus were more susceptible to interference from a concurrent visuo-spatial task than an auditory suppression task, suggesting that a spatial representation of the problem state might be the underlying mechanism in their encoding framework.

Oulasvirta & Saariluoma (2006) investigated the viability of using LTWM to explain interrupted task performance by testing the abilities of skilled readers to remember the semantic context of expository texts. They observed that regardless of pace, intensity, or difficulty, interruptions did not contribute negatively to comprehension. However, when the stimuli were presented at the limit of perceptual encoding, interruptions negatively impacted performance. Thus, when applied to the concept of interruptions, these findings and the theory of LTWM suggest that, as long as task demands do not exceed encoding speed, experts on a task should be better able to protect against interruptions by being able to rapidly encode more information into the protected LTWM store.

Memory for Goals

The Memory for Goals model is a theory of interrupted task performance that has roots in the ACT-R cognitive framework (Altmann & Trafton, 2002). Essentially, a task that is being worked on is broken down into its simplest goals and sub-goals, with each component being a goal. The higher the level of activation of a particular goal, the more likely it is to fire, and thus be executed. The first constraint of Memory for Goals is that this activation, however high it is, must be higher than the current level of interference, which is the clutter of residual memories in the memory system. Once activation exceeds this level, work on the goal can commence.

The second constraint of Memory for Goals, known as strengthening, uses the rate at which a goal is sampled to determine the level of activation of a goal. Key to this constraint is that it addresses the issues of proactive interference, where a new goal will experience increased interference from old goals, and feedforward, where an activated goal continually self-strengthens at the same time. The third and final constraint, priming, suggests that cues of any type can be used to help boost activation of an old goal.

Applied to interrupted task performance, Memory for Goals sees the primary task as one goal and the interrupted task as a new goal. When interrupted, decay of the activation associated with the original goal starts to occur, as strengthening is devoted to the activation of the new goal. As the interrupted task is completed, cues such as the completion of the interrupted task prime the activation of the original goal, leading to resumption of the primary task. The strength, number, and quality of these cues determine whether the original goal received enough activation to exceed interference and trigger resumption.

Threaded Cognition

In conjunction with Memory for Goals, Threaded Cognition is a theory of multitasking performance that is similarly rooted in ACT-R. The foundation of threaded cognition revolves around a serial processing system that manages specific perceptual resources, like auditory or visual tasks, collecting information from these resources or redirecting information to other resources. Salvucci and Taatgen (2008) use the elegant analogy of a cook in a kitchen, required to prepare multiple meals. The cook, they explain, is the processing system, with kitchen tools, like the oven or mixing machine in a kitchen, as the perceptual resources, and food orders as tasks or goals that the system must perform (Figure 1).

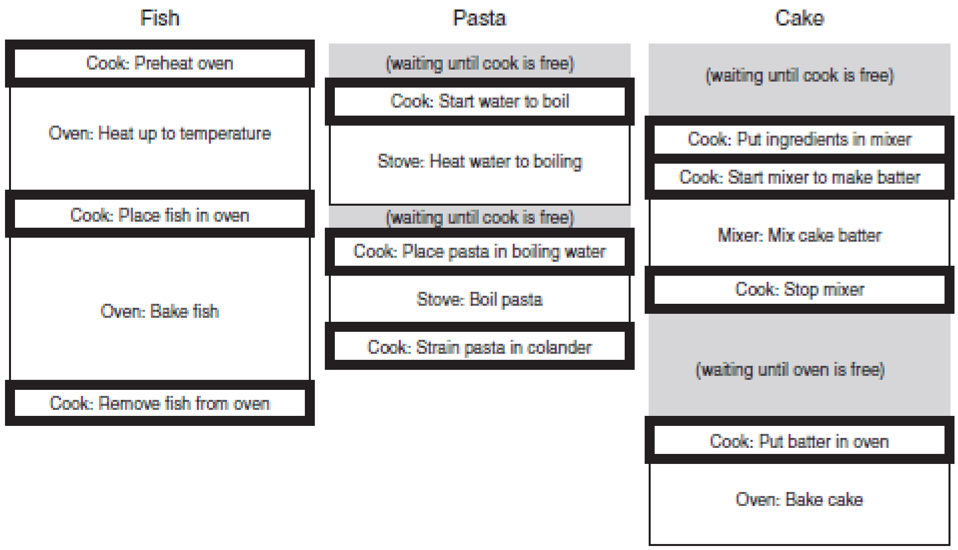

Figure 1. An example of Threaded Cognition using a cooking analogy (Salvucci & Taatgen, 2008).

Applying Threaded Cognition to the concept of interruptions using a traditional interruption paradigm like the one shown in the anatomy of an interruption (Boehm-Davis & Remington, 2009), there are only two threads for the primary and interrupting tasks, and only two switches, one from the "primary" thread to "interrupting" thread, and then back to the "primary" thread. In complex interrupted situations, though, there can easily be more threads and more switches between threads.

Role of Memory for Spatial Location in each theory

Although Long-Term Working Memory, Memory for Goals, and Threaded Cognition outline a task-interruption framework, none seem to address the role that memory for spatial location might play in the resumption process. With Long-Term

Working Memory, memory stores are not broken down into modalities like the original working memory concept (visuospatial sketchpad and phonological loop); rather, all information is treated as chunks of memory to encode. This approach is problematic, though, as research in implicit memory has shown that even though recognition of a given spatial configuration is only at chance, participants exhibited improved visual attention, detecting targets in learned configurations more quickly (Chun & Jiang, 1998). If there are indeed separate memory stores, rather than just one, Long-Term Working Memory would initially not be a good fit when attempting to explain the role of an intact spatial representation in an interruptions framework.

Resumption from interruptions in Threaded Cognition centers on the use of a "problem state" resource, which is a single-chunk storage component in working memory. When this resource is required by multiple tasks, as is the case with interruptions, resumption performance is impacted. However, Borst, Buwalda, van Rijn, & Taatgen (2013) observed that external cues can be used to provide support to the problem state, allowing the "problem state" resource to be maintained during an interruption, resulting in improved performance. Unfortunately, while the research by Borst et al. does use external cues, these cues are semantic in nature, and do little to speak to any role spatial memory might play here.

Initially, Memory for Goals made no explicit mention of the role of an intact spatial representation in interruption resumption. However, the role of spatial memory in interruptions was later investigated when Ratwani & Trafton (2006) examined the nature of eye-movements when recovering from an interruption. They found that participants were generally able to fixate in the region where they left off. Next, they manipulated the availability of the primary task through the interruption, showing that an available spatial representation of the task throughout the interruption period lead to improved recovery (Ratwani, Andrews, McCurry, Trafton, & Peterson, 2007). Finally, they tested the susceptibility of spatial memory to interference using a spatial interrupting task, concluding that resumption from interruptions was negatively affected when spatial memory was disrupted. This body of work led the authors to conclude that spatial memory is a mechanism used to resume from an interrupted task, and that spatial memory could be integrated into Memory for Goals using the same priming mechanism used for environmental cues (Ratwani & Trafton, 2008).

Based on the research by Ratwani & Trafton, the focus of this work will further investigate the role that spatial memory for location might play in interruption resumption, and whether such a mechanism might actually be used to help mitigate the effects of interruptions. In order to assess this, specific hypotheses were formed. Based on previous research, we hypothesize the following:

1. When the location of the primary task changes from one location prior to an interruption, to a new location following the interruption, the negative effects of an interruption will be exacerbated.
2. Participants will leverage any memory for spatial location by saccading to, or fixating near, the pre-interruption location of the primary task if it is not yet visible.

3. Participants will be able to successfully report pre-interruption primary task locations.
4. Post-interruption performance will be affected by pre-interruption location strengthening; as participants experience a task being presented constantly in one location, primary task location changes will be more detrimental to performance.
5. Post-interruption performance will be affected by post-interruption location strengthening; as participants experience a task resuming in a constant location, resumption performance will improve.

In addition, based on previous research, we hypothesize the following:

6. Participants who are interrupted at a task breakpoint will show attenuated decrements compared to those who are interrupted while working on a task.
7. Any observed effects of delay and/or change, particularly those regarding the effect of change, will be agnostic to the interrupting task.

The proposed research will address these questions and provide more insight on any role memory for spatial location plays in interrupted-task environments, and whether it can be better leveraged to provide increased resilience to the deleterious effects of interruptions.

Experiment 1

The purpose of Experiment 1 is to validate and replicate previous research on the role of memory for spatial location in interruptions by leveraging Ratwani & Trafton's work (2006) on eye-movement behaviors following an interruption, and how delay and/or primary task location changes impact post-interruption performance. If the task changes location prior to resumption, task performance metrics like correct responses, completion times, and resumption lags will be negatively impacted, more so than if the primary task did not change location following an interruption. Furthermore, if participants are leveraging their memory for spatial location of the task, gaze data should show participants returning to the previous location of the primary task following interruption resumption.

Methods

Participants

Nine undergraduate and graduate students from George Mason University participated for either research credit or financial remuneration. Participants were required to have normal or corrected-to-normal vision without the use of glasses.

Task and Materials

The primary task for Experiment 1 is a heavily modified version of the Quadrant paradigm originally developed by Werner, Cades, Boehm-Davis & Peterson (2009), where participants are required to perform a primary task in one quadrant of the screen while possibly being interrupted by a different task that occludes the whole screen. In this experiment, the primary task consisted of a simple vertical addition problem with 3 addends, two of which were 7 digits, while the third addend ranged between 5 and 7 digits (Figure 2). For the interrupting task, a simple multiple object tracking (MOT) paradigm (Pylyshyn & Storm, 1988) was used (Figure 3).

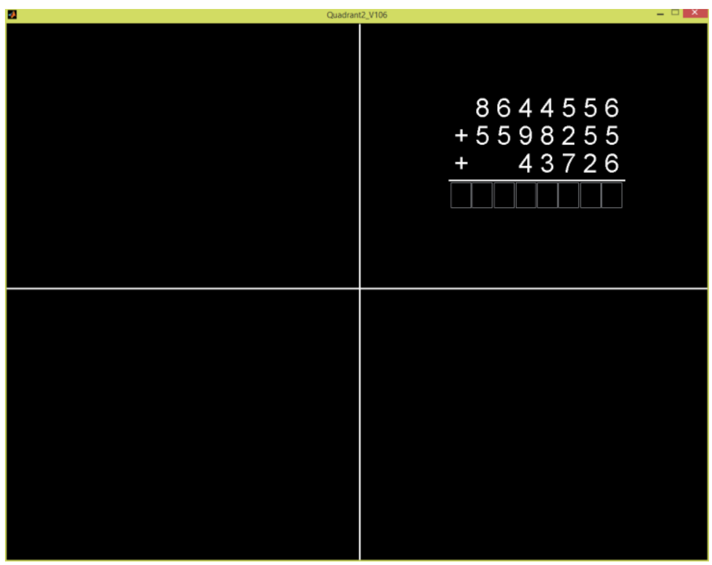

Figure 2. Example of the Quadrant paradigm, with the primary task visible.

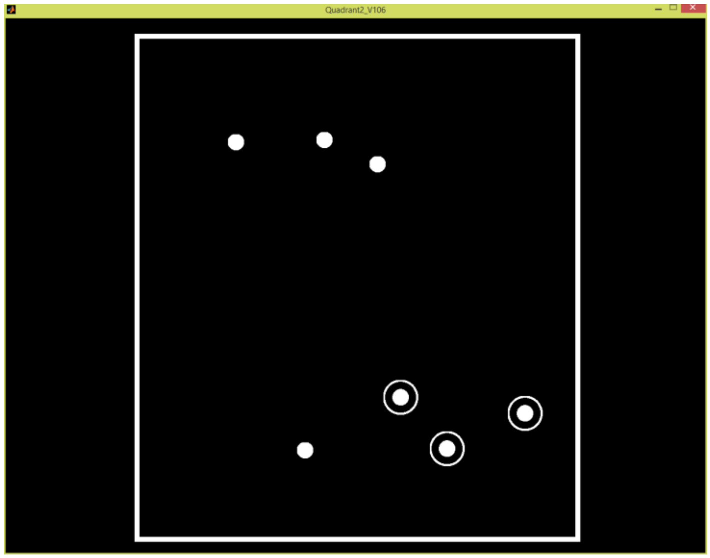

Figure 3. Example of the Quadrant paradigm with the secondary task visible.

Two computers were used in this study, one for stimulus presentation and one for the acquisition of eye-tracking data. The computers were networked using a serial port in order to transmit "start" and "stop acquisition" signals from the task computer to the acquisition computer. The experimental task was 1281x1008 pixels and was displayed on a 23", 120 Hz. LCD monitor with a 1920x1080 resolution. Any area on the screen not taken up by the task was displayed as a black background.

Eye-tracking data were acquired using a Tobii X60 table-mounted infrared eye-tracker with a sampling rate of 60 Hz. Data were acquired using a custom MATLAB application written with dynamic link libraries provided in the Tobii software development kit.

Finally, a simple demographics survey allowed participants to report their age, gender, class, and first language.

Design

All addends for the primary task were randomly generated, with the lone requirement for each problem being that the sum of every column must involve carrying a number over, ensuring that following each interruption, there is the potential for an error. Participants were instructed prior to the start of the experiment that they should click in the dialog box at the bottom of each column, then perform the math problem in their head, enter the response, and then press the "Enter" key on the keyboard. They were to repeat this process for each of the following digits. This "click, think, respond, enter" framework allowed us to ensure that participants were completing the addition problems sequentially.

The primary task was designed such that interruptions could be triggered either by time or by the completion of a certain column of the math problem. For time triggers, each interruption was scheduled to occur at a random time between 12 and 21 seconds. For column completion triggers, participants were randomly interrupted after completing the 3^{rd}, 4^{th}, 5^{th}, or 6^{th} column of a given problem. Thus, if a trial was scheduled to be interrupted after completing the 5^{th} column or after 17 seconds of elapsed time on that trial, the interruption was triggered by the requirement that was met first. This design introduced a great degree of variability in when an interruption occurred, making them much less predictable than if the interruptions were solely column- or time-based.

However, it should be noted that this dichotomy in how the interruption is triggered effectively produces two levels of interruption difficulty. Interruptions that are column-triggered occur at what is essentially a mini-breakpoint in the primary task due to the completion of a sub-goal, i.e. the completion of one column. These interruptions stand in stark contrast to time-triggered interruptions, which do not occur at a “good” point. Effectively, these interruptions remove participants in the middle of their thought process and transition them to the interrupting task, where upon completion of the interruption they’ll then need to re-engage, likely resulting in the need to restart work on that column. As a result, for analyses purposes, all analyses will be examined through the lens of how the interruption was triggered, in addition to any other experimental factors.

When an interruption occurred, the quadrant framework disappeared and participants were presented with a 792x905-pixel rectangle containing 7 white dots with a diameter of 30 pixels signifying the start of the interrupting task. Participants were cued to three of these dots for a total of 2 seconds before the cue disappeared and the dots began to move. It is important to note that the dots only reached their maximum speed after two seconds of movement; this was designed to make the start of each trial less jarring. The total duration of each interruption was 20 seconds, upon which the dots stopped and participants indicated which of the 7 dots were the three cued at the start of the interruption by clicking on them. Participants were provided with auditory feedback for each response, with correct or incorrect selections accompanied by either a high or low beep, respectively.

The two experimental factors for Experiment 1, resumption display delay and resumption location change, were unique to interrupted trials. The first factor, resumption display delay, describes whether there was a 500-millisecond delay between when the interruption completed (and the quadrant dividers/crosshairs reappear), and the addition problem actually appeared. The second factor, resumption location change, describes whether the addition problem appeared in a quadrant different post-interruption than the one it was in prior to the interruption. These factors were completely crossed, allowing for four unique experimental conditions for the interrupted trials.

Participants completed a total of 80 trials with 40%, or 32 trials, being interrupted. Of these 32 trials, 8 were assigned to each of the four experimental conditions, with 2 trials starting in each quadrant.

Procedure

Upon completion of a training PowerPoint which emphasized the “click, think, response, enter” framework, participants were given three practice trials to expose them to the task. At the end of the three trials, participants were asked if they felt ready or if they required an additional three practice trials. Participants then started the task. They were provided with three 90-second breaks, which occurred after the completion of trials 20, 40, and 60. During the break, participants were able to see the time remaining before the break ends, but were encouraged to rest, stand up and stretch, or close their eyes. Participants were instructed that after 80 seconds, they would be warned with an auditory tone that the task would be resuming shortly; this was to discourage them from simply watching the clock so that the break time could actually be used to relax. Participants were not informed of these breaks during training and were informed of their progress throughout the experiment. When the trials were completed, participants were asked to complete the short demographic survey previously mentioned.

Results

Post-Interruption Response Errors

The first analysis focused on the accuracy of participant responses. A 2x2 Repeated Measures ANOVA analyzing the effects of delay and change was performed using only the responses on columns that immediately followed an interruption. This analysis produced a significant effect of change ($F(1, 8) = 10.667$, $p < .011$), with participants exhibiting an 8% decline in correct responses when the task changed location as opposed to when it did not change location following an interruption (Figure 4).

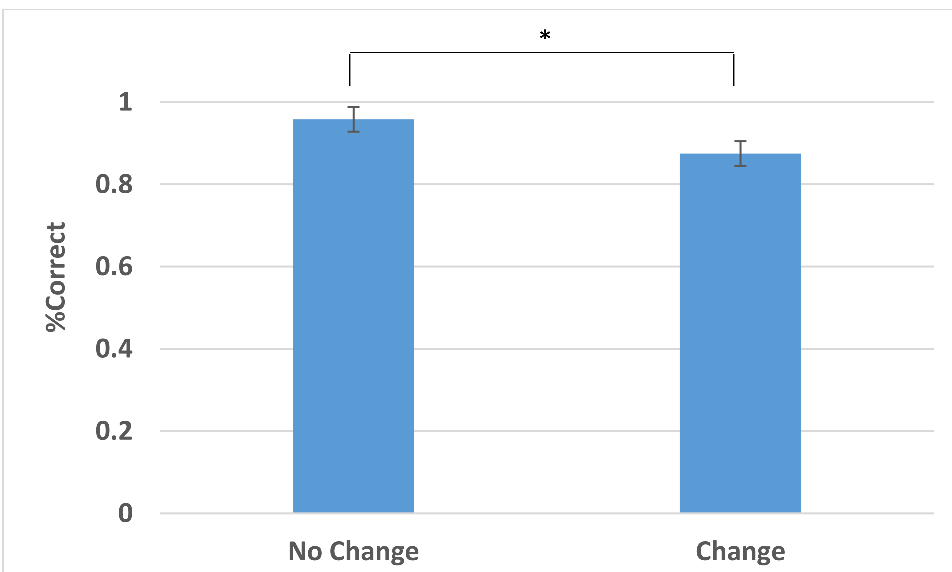

Figure 4. Percentage of correctly-entered digits immediately following an interruption for the "No Change" and "Change" conditions. Error bars are 95% CIs.

Further analysis was conducted to identify the exact locus of the performance decrement. Specifically, the responses of each participant were analyzed to see if their responses were simply the result of them failing to include the carry-over number in their calculation for that digit, or if there was some other reason for the mistake. The results of this analysis indicate that the difference between the no change and change conditions seems to be driven by the rate at which unexplained errors are committed ($F(1, 8) = 6.000$, $p < .04$), not by the rate at which participants simply forget to carry ($F(1, 8) = 1.333$, $p > .05$). The difference in the no change and change conditions when accounting only for forgotten carryovers is only 2%, while the difference for same conditions account only for unexplained errors is about 8% (Figure 5).

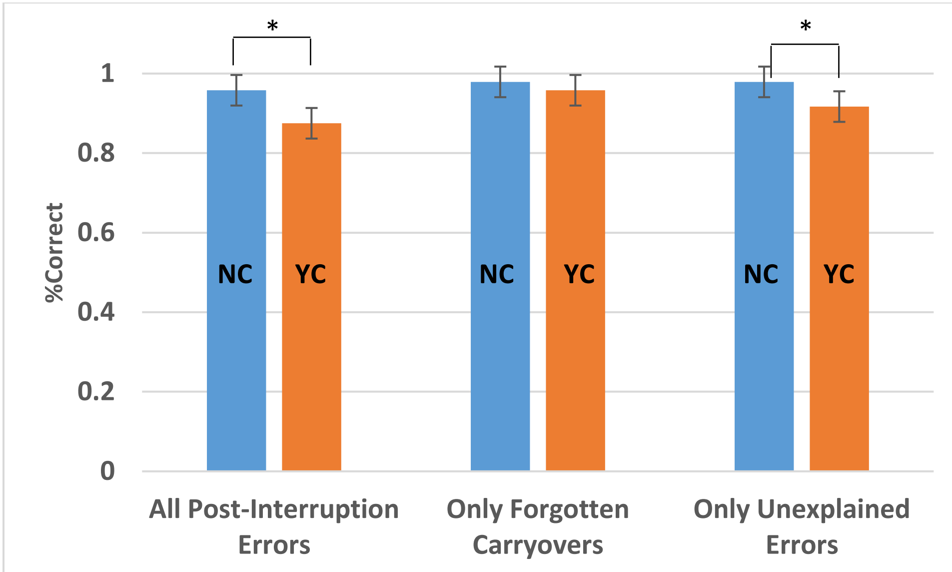

Figure 5. Percentage of correctly-entered digits immediately following an interruption between no change (NC) and change (YC) conditions account for all errors, only forgotten carryovers, and only unexplained errors. Error bars are 95% CIs.

These results seem to suggest that changing the location of the primary task causes a more disruptive effect than if the participant was simply interrupted, and that this effect is not isolated to a failure to recall all necessary information required for error-free resumption.

Resumption Lags

The timing data were found to be highly skewed with some extreme outliers. Therefore, the data were transformed using a reciprocal transformation for purposes of analysis. All graphs are displayed using back-transformed means and confidence intervals.

An analysis of participant resumption lags, or the time interval separating the end of the secondary task and the first subsequent action taken by the operator in the primary task (Altmann & Trafton, 2004), found an interaction between task display delay and location change (*F(1,8)* = 6.551, $p < .035$).

The interaction indicated that when no delay was available to recover from the interruption, there was a significant difference in resumption lags between the no change and change conditions, with change conditions resulting in higher resumption lags (Figure 6). However, when there was a 500 ms delay, changing the task location upon resumption did not affect resumption times. This result echoes the performance findings, which support the highly disruptive nature of changing the location of the task.

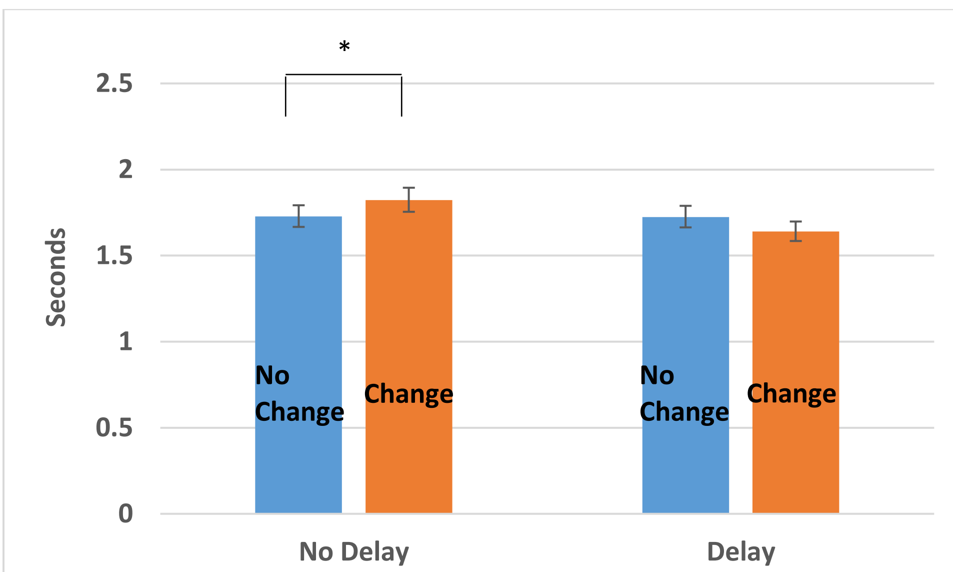

Figure 6. The display delay-by-location change interaction for resumption lags. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

Inter-Action Intervals

In addition to resumption lags, the lag times between completion of one column of the math problem and engagement of another column of the math problem, known as inter-action intervals (IAIs), were analyzed. IAIs were broken down across display delay, location change, and interruption triggers, as well as prior to and following an interruption. Only a main effect of trigger was significant ($F(1,7) = 6.760$, $p < .035$, Figure 7), indicating that trials with interruptions that were triggered by column completion resulted in longer average IAIs than interruptions that were triggered by time.

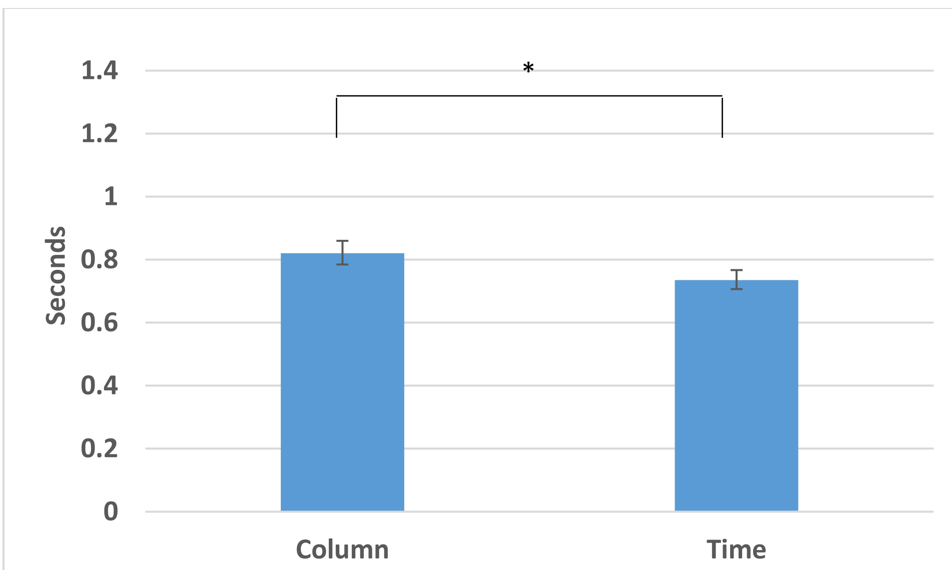

Figure 7. The main effect of interruption trigger type (column or time) on inter-action intervals (IAIs). Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

Post-Interruption Completion Times

A 2x2x2 Repeated Measures ANOVA analyzed the effects of interruption trigger, delay, and change, respectively on average column completion times. A significant main effect of trigger ($F(1,7) = 16.485$, $p < .005$) was observed, with significantly slower object completion times observed for time-triggered interruptions compared to column-triggered interruptions (Figure 8).

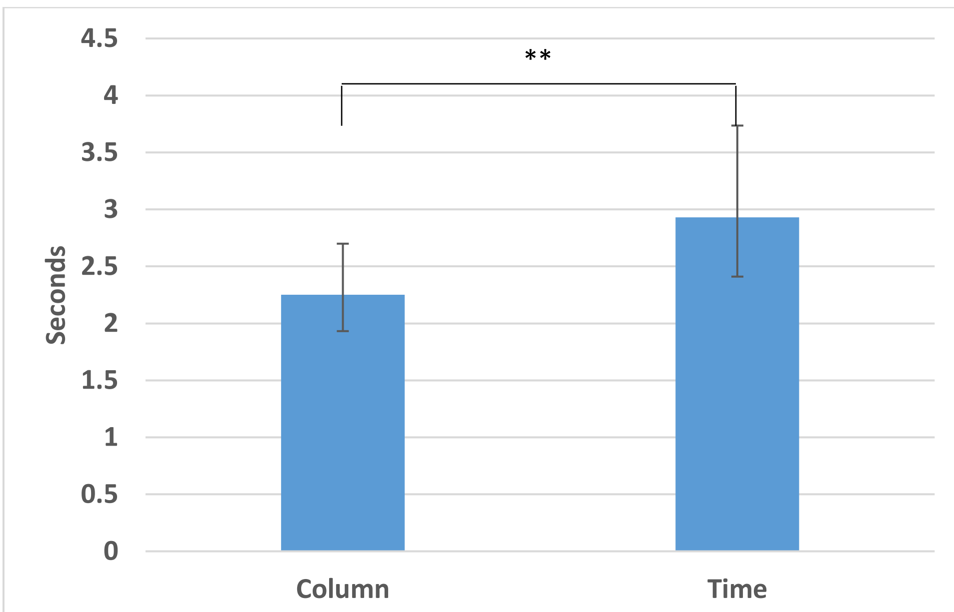

Figure 8. Average column completion times following column- and time-triggered interruptions. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

The second significant effect in this analysis was a significant interaction between change and delay for post-completion times ($F(1,7) = 5.868$, $p < .046$). Similar to the resumption lag analysis, average completion times differed between the no change and change conditions when no delay was present. However, when a delay was present, there were no differences in average completion times following an interruption (Figure 9).

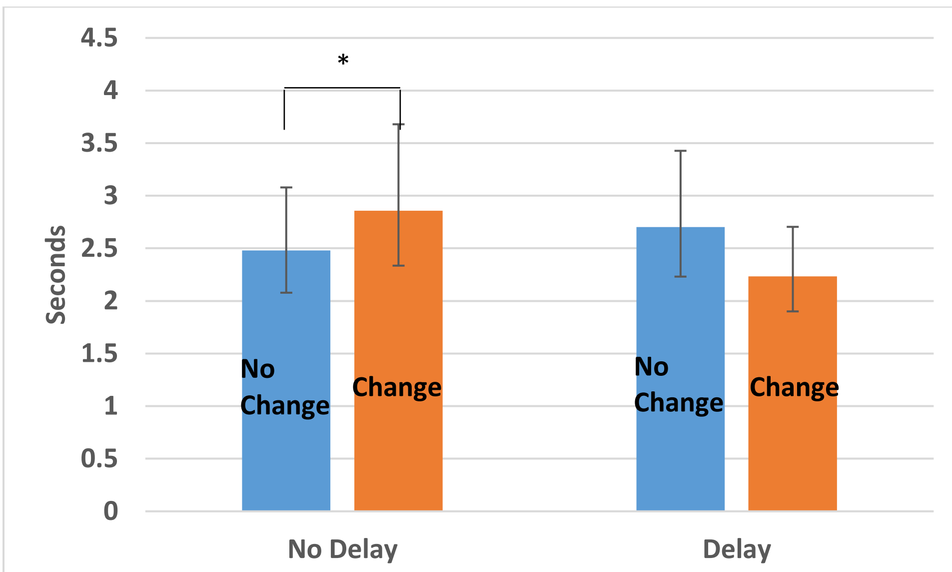

Figure 9. Average post-interruption completion times for the no change and change conditions as a function of delay. Error bars are 95% CIs. Displayed means and error bars are back-transformed to original units.

The third significant effect was a significant 3-way interaction between trigger, change, and delay ($F(1,7) = 14.986$, $p < .006$). Decomposing this interaction yielded an effect identical to the previous delay-by-change interaction, with “no delay” trials exhibiting higher completion times when the task location changes ($F(1,7) = 8.948$, $p < .02$), and “delay” trials exhibiting lower completion times when the task changes location ($F(1,7) = 12.656$, $p < .009$). However, this effect was isolated only to interruptions triggered by column (Figure 10). Interruptions triggered by time exhibited no differences between delay and change conditions (Figure 11).

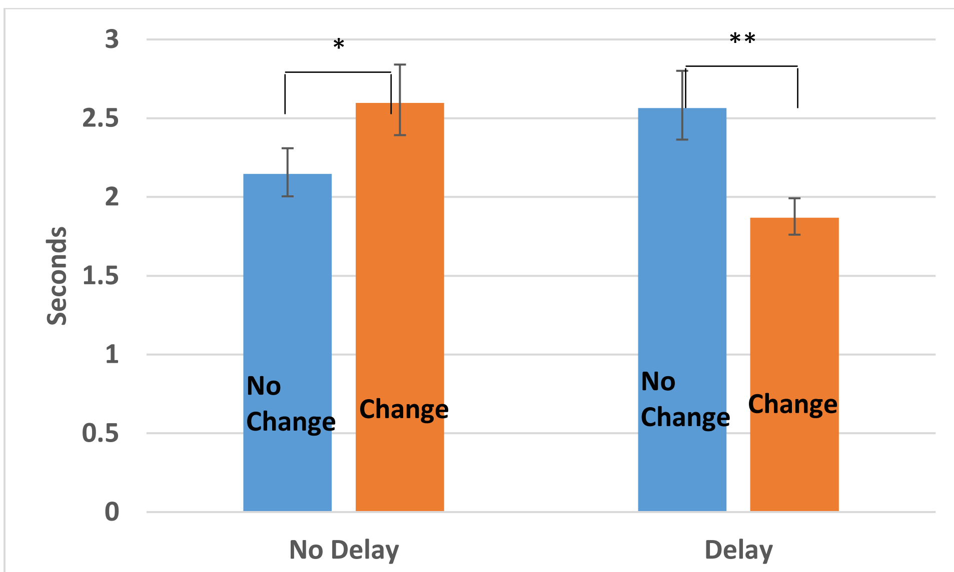

Figure 10. Average post-interruption completion times for interruptions triggered by column, broken down by delay and change conditions. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

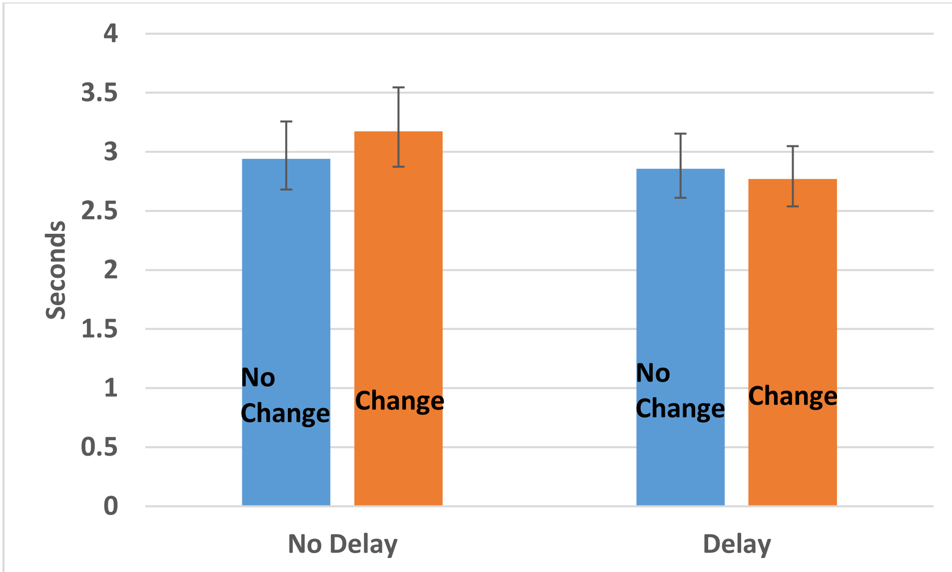

Figure 11. Average post-interruption completion times for interruptions triggered by time, broken down by delay and change conditions. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

Eye-Tracking Data

One area of particular interest is the initial eye-movement behaviors immediately following the completion of the interruption and return to the primary task. Specifically, we wanted to know if participants returned to the quadrant they were previously working in, as was suggested by previous research (Ratwani & Trafton, 2006) or if they exhibited a random scan or static gaze until they directly shifted attention induced by the reappearance of the task.

The use of serial triggering allowed the eye-tracking data to be partitioned into all of the components of an interrupted trial (pre-interruption, interruption, post-interruption) prior to analysis. Data were then filtered for acquisition errors (participants looking off screen, bad quality values), as well as participant blinks or eye closures. Next, data were classified using a slightly modified version of the I-DT fixation classification algorithm (Salvucci & Goldberg, 2000), which used positional dispersion coupled with a temporal component to classify raw gaze values into fixations. Specific modifications include the use of Euclidian distance calculations for dispersion, as opposed to the additive x-axis and y-axis dispersion originally specified by Salvucci & Goldberg, and a single-bad-point bypass, which allows the algorithm to continue classification of a specific fixation window if a single bad point occurs during that window. Finally, point-to-point velocities were represented over time and imported to an algorithm that would identify peaks and the derivatives around those peaks. Peaks representing velocities in excess of 70^{o}/second were classified as potential saccades, with the changes in direction of the curve prior to and following those peaks representing the start and end of the saccade. Only curves with continuous quality data from the beginning to the end were ultimately classified as a saccade.

Specific details regarding how eye-movements were classified can be found in Appendix A. However, for purposes of this paper, the expected gaze behaviors, where participants eye-movements showed evidence of returning to the previous task location, and unexpected gaze behaviors, where participants eye-movements did not show evidence of returning to the previous task location, were tallied using both strict and liberal classification methodologies.

Once the counts were tallied, two one-sample *t*-tests were performed, comparing the expected gaze behaviors for each methodology against the computed likelihood for each methodology. These values were computed by taking the proportion of area on the screen classified as an expected gaze behavior ($\pi * 200\ pixels^2$ and $\pi * 250\ pixels^2$ for the strict and liberal methodologies, respectively) to the area of the entire Quadrant task ($1281\ pixels * 1008\ pixels$).

Using the strict classification methodology, the number of expected gaze behaviors were not significantly different from the chance value of 9.73% ($t(8) = -1.579$, $p < .153$, Figure 12). When using the liberal methodology, expected gaze behaviors were actually significantly below the chance value of 15.21% ($t(8) = -3.65$, $p < .006$, Figure 12). These results clearly indicate that participants did not return to the previous task location following an interruption.

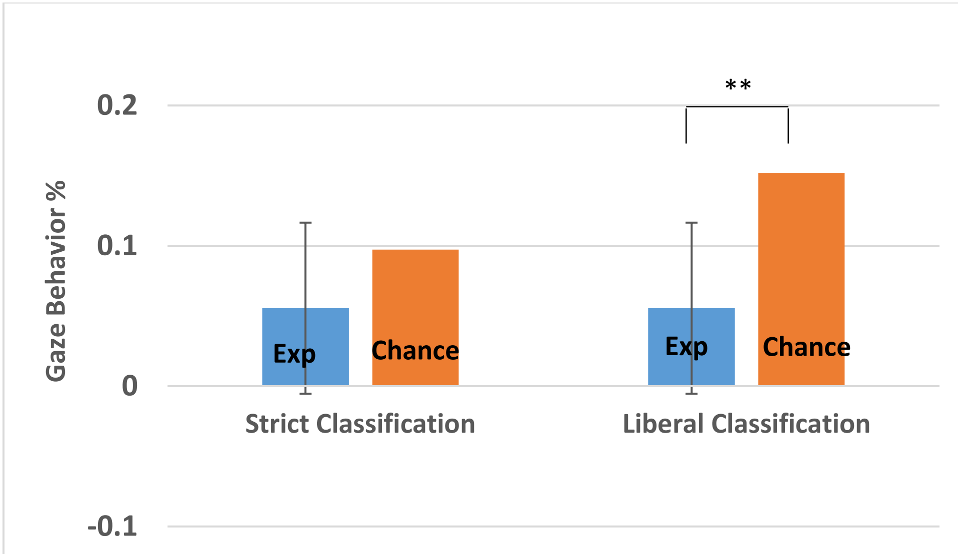

Figure 12. Comparison of gaze behaviors classified as expected gaze behaviors ("Exp") vs. computed chance values for strict and liberal classifications. Error bars are 95% CIs.

Discussion

Table 1. Results summary for Experiment 1.

Results Summary	
Measure	Exp. 1
Post-Interruption Errors	*No Change < Change*
Resumption Lags	For No Delay: *No Change < Change*
Inter-Action Intervals	*Time Trigger < Column Trigger*
Post-Interruption Completion Times	*Column Trigger < Time Trigger* For No Delay: *No Change < Change* For Column Trigger*No Delay: *No Change < Change* For Column Trigger*Delay: *No Change > Change*
Gaze Behavior	For Strict: *Expected = Chance* For Liberal: *Expected < Chance*

Although it has been known for some time that interruptions are disruptive, the negative impact on performance when the primary task shifts location, even just a few inches horizontally and/or vertically, is fascinating.

In this experiment, changing the task location upon resumption caused an 8% increase in errors on the first column immediately following an interruption (Figure 4). What's even more striking about this finding is that these small changes in location seem to disrupt participants to the point that they make mistakes that go beyond simply forgetting to carry-over (Figure 5). Such a finding underscores two points; first, interruptions degrade performance beyond the time cost. Second, memory for spatial location appears to play some role in interruption resumption, given the decrements in performance observed when the task changed location.

The results of the timing data follow one distinct trend; the interaction between delay and location change. When no delay occurs between the end of the interruption and primary task resumption, resumption lags and average post-interruption completion times exhibit decrements when the task changes location. When a delay is present, there are no differences between whether the task does or does not change location. These results indicate that even a delay as short as 500 ms is enough to mitigate the observed time decrements when the task changes location.

Finally, the method by which an interruption is triggered appears to have differential effects on task performance. With regard to average inter-action intervals and average completion times, the interruption trigger modality has a main effect, with participants spending less time between columns and more time in columns when an interruption was triggered by time. Recall that interruptions could either be triggered by completing a specific column or by reaching a specific point in time, and this difference in how interruptions were triggered introduces different difficulties. The first trigger type, column, would be considered the less disruptive of the two types of interruptions, as this interruption occurs at a natural break in the workflow, i.e. when participants are moving from one column to another. The second trigger type, time, certainly would be the more disruptive of the two, as it occurs while participants are still working inside a given column. This more disruptive type of interruption seems to cause increased time pressure, something that while increasing the speed at which participants interact with the task, does not improve performance, as evidenced by the longer completion times.

The interaction between trigger type, delay, and location change on average completion time continues to support this narrative. When an interruption is triggered by column, the delay-by-change interaction behaves similarly to the previously discussed delay-by-change interactions, with the addition of an odd improvement in performance. This improvement was reflected by the decrease in average completion time when there is a change in task location compared to when there is not (Figure 10). Interruptions triggered by time, however, show no change or delay effects, but average completion times are all at least 500 ms greater than their column counterparts. It's possible that time-triggered interruptions are so taxing that any subtle change or delay effects are eliminated, and that a ceiling effect takes place due to the cognitive difficulty. It is also possible that, because the trigger type is not an experimentally-controlled variable but rather a pseudo-experimental variable, there are there are sampling differences which are artificially influencing this effect. This possibility is supported by the comparison of the frequencies of column-triggered and time-triggered interruptions, where approximately 60% of interruptions were time-triggered.

The gaze movement analyses were designed to see if, during the delay period, participants were showing any signs of memory for the location of the task. The results suggest that, at best, indicators of memory for spatial location exhibited by gaze behaviors are only present 10% of the time. There are a few possible reasons for this result.

First, data quality for the eye-tracking was an issue; people tended to blink during the delay period, resulting in large portions of the 500 ms delay period consisting only of blink time. It is possible that a longer delay window here would alleviate this concern.

Second, it is possible that participants decided that returning to the center was the best way to hedge their bets. Theoretically, if participants were to saccade or fixate to the location of the task prior to an interruption, they would be correct only 50% of the time (correct on all of the no change trials). This would be significantly better than selecting a random location (25% chance of guessing correctly). However, it should be pointed out that participants did not know how often the task would change location; the data suggest that they decided to stare at the center of the screen.

In conjunction with the possibility that participants were hedging their bets, there is the possibility that participants did not find it useful to return to the previous location. Given the number of interruptions that occur in the study and the number of times the primary task changed location, participants may have felt that the task's behavior was too random to reliably predict. This randomness resulted in relatively weak priming of any one location, and as such, participants ended up resting at center.

Third, it is possible that the design of the interface, i.e. the crosshairs in the middle of the screen, actually contributed to participants fixating at the center by serving as a de facto fixation cross. Although this was originally included to provide clear boundaries between the four quadrants, it is possible that this had an unintended effect with regard to eye-movements.

Finally, it is possible that participants simply did not have any conscious knowledge of where the task was located. Participants were not told in advance they needed to remember exactly where the task was prior to the interruption, so they may have not encoded that information, instead opting to just resume whenever the task reappeared. In essence, they may have let the task reappearance prime their goal memory. This scenario could actually still provide evidence for the concept of memory for spatial location, though, as the decrements observed when the task changed location suggest that memory for spatial location may, while not standing on its own, serve to help strengthen goal activation. However, it should be noted that this seems somewhat at odds with the performance decrement observed when the primary task changes location following an interruption. If the reappearance of the task was the sole factor in priming resumption, no differences between the change conditions should be observed. This possibility is directly tested in Experiment 4.

Experiment 2

Given the number of questions raised by Experiment 1, several more experiments were devised to continue to examine the role that memory for spatial location might play on interruption resumption. The focus of Experiment 2 was to remove the quadrant divider/crosshairs from the first experiment and see if performance, timing, and most importantly, gaze behavior data changed. This change is the sole difference between Experiment 1 and Experiment 2. As was the case in Experiment 1, if the task changes location prior to resumption, task performance metrics like correct responses, completion times, and resumption lags will be negatively impacted, more so than if the primary task did not change location following an interruption. If participants are leveraging their memory for spatial location of the task, gaze data should show participants returning to the previous location of the primary task following interruption resumption.

Methods

Participants

Seventeen undergraduate students from George Mason University participated in the study for course credit. Three participants were excluded due to math task performance that fell below 90%. Of the 14 participants who were included in the behavioral analyses, 10 were included in the eye-tracking analysis.

Results

Post-Interruption Response Errors

No significant main effects of delay ($F(1,13) = 4.452$, $p < .055$), change ($F(1,13) = 1.413$, $p < .256$), or interactions ($F(1,13) = 2.403$, $p < .145$) were observed for post-interruption response errors across experimental conditions.

Resumption Lags

No significant main effects of delay ($F(1,13) = 1.118$, $p < .310$), change ($F(1,13) = .288$, $p < .601$), or interactions ($F(1,13) = 1.334$, $p < .269$) were observed for resumption lags across experimental conditions.

Inter-Action Intervals

No significant main effects of delay ($F(1,13) = 1.586$, $p < .230$), change ($F(1,13) = .001$, $p < .981$), or interactions ($F(1,13) = .505$, $p < .490$) were observed for inter-action intervals across experimental conditions.

Post-Interruption Completion Times

With regard to the significant main effect of trigger ($F(1,13) = 7.031$, $p < .020$), the data follow the previous trend observed in Experiment 1; that is, average post-interruption completion times are greater for interruptions triggered by time than by column (Figure 13).

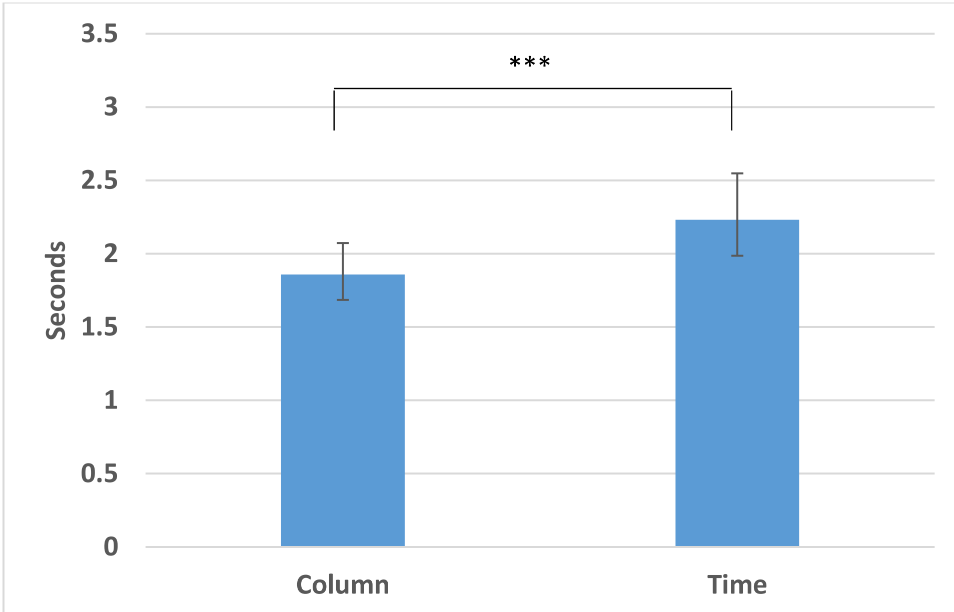

Figure 13. Average column completion times following column- and time-triggered interruptions. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

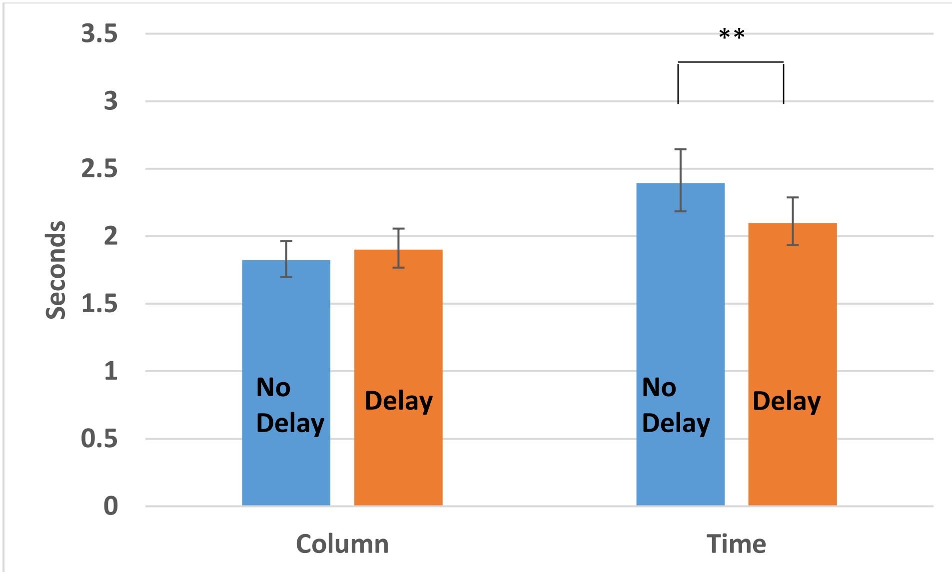

Figure 14. Average post-interruption completion times for column- and time-triggered interruptions for no delay and delay conditions. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

Eye-Tracking Data

Eye-tracking data were analyzed using the same procedure as in Experiment 1.In this experiment, analyses of both strict ($t(9)$ = 1.38, p < .201, *Figure 15*) and liberal ($t(9)$ = .061, p < .953, Figure 15) classification methodologies indicated that expected gaze behaviors did not significantly differ from their respective chance values.

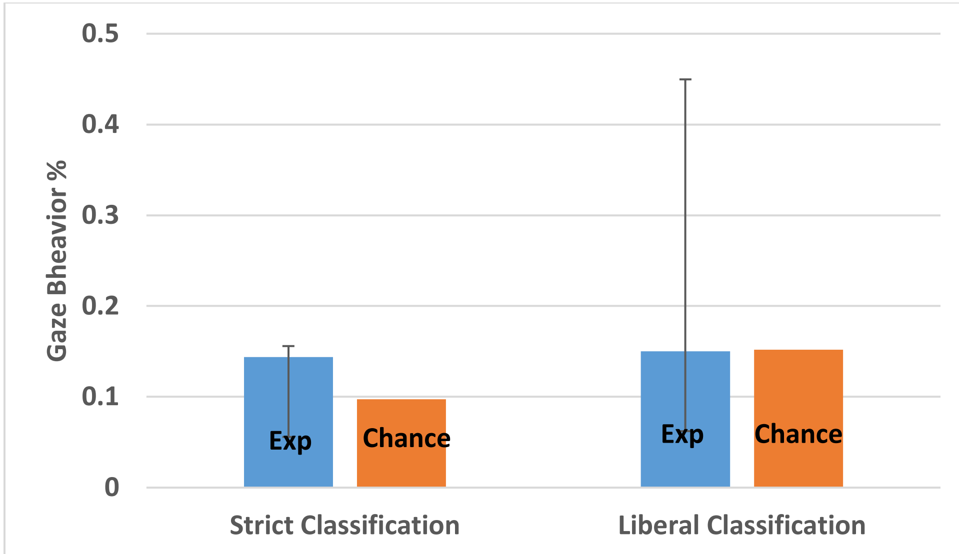

Figure 15. Comparison of gaze behaviors classified as expected gaze behaviors (“Exp”) vs. computed chance values for strict and liberal classifications. Error bars 95% CIs.

Discussion

Table 2. Results summary for Experiment 2.

Results Summary	
Measure	Exp. 2
Post-Interruption Errors	*NSF*
Resumption Lags	*NSF*
Inter-Action Intervals	*NSF*
Post-Interruption Completion Times	*Column Trigger* < *Time Trigger* For Time: *No Delay* > *Delay*
Gaze Behavior	For Strict: *Expected* = *Chance* For Liberal: *Expected* = *Chance*

Through the lens of Experiment 1, the results in Experiment 2 are difficult to interpret. The removal of the quadrant divider from the window produced some results that were certainly not what was expected, as the post-interruption error and resumption lag effects observed in Experiment 1 were no longer observed. These were two key measures of the negative effects of interruptions observed in the previous experiment.

Additionally, the interaction between interruption trigger and delay on average post-interruption completion time is perplexing. In this experiment, for time-triggered interruptions, trials in which no delay occurred exhibited longer completion times than trials in which a delay did occur, something that runs counter to predictions made by Memory for Goals, Long-Term Working Memory, and Threaded Cognition.

Consistent between Experiments 1 and 2 is the gaze behavior analysis. Experiment 2 data continue to make the argument that participants are not exhibiting any outward signs of memory for spatial location prior to task resumption. However, while we were able to address the possibility that the design of the interface was the cause for the lack of preemptive eye-movements, concerns such as participant blinks/length of the delay window, hedging/poor location priming, and conscious knowledge, are all things that have not yet been addressed.

Across the first two experiments, interruption trigger continues to be a significant factor in a number of analyses between the Experiments 1 and 2, and it certainly is clear that time-triggered interruptions produced decrements compared to column-triggered interruptions. However, the exact nature of those decrements is less clear, with trigger playing a role in performance, inter-action interval, and average object completion time.

So, the question becomes; why were effects found in Experiment 1 so different than those of Experiment 2? Why would the removal of the quadrant dividers have a massive effect on the delay-change paradigm, but only for column-triggered events? As there does not seem to be any theoretical basis for why such a minute change would result in such a shift in results, for now, sampling error seems like the only plausible explanation.

Experiment 3

Another question that was raised by Experiment 1 was whether the lack of expected gaze behaviors could be due to spatial memory being overly taxed. Although it is somewhat obvious that the interrupting task is spatial in nature, there is also a component to the primary task that is inherently spatial in nature (Meyer, Salimpoor, Wu, Geary, & Menon, 2010). As a result, Experiment 3 is a repetition of the previous experiment, but with an interrupting task that contains no spatial components in order to understand the role an interrupting task of a different modality might play in the Quadrant paradigm. The purpose of this study is to replicate Experiment 2, but with an auditory N-back, where the spatial memory demands are far lower than in the previous experiments. As was the case in previous experiments, if the task changes location prior to resumption, task performance metrics like correct responses, completion times, and resumption lags should be negatively impacted, more so than if the primary task did not change location following an interruption. Furthermore, if participants are leveraging their memory for spatial location of the task, gaze data should show participants returning to the previous location of the primary task following interruption resumption.

Methods

Participants

Twenty-six undergraduate students from George Mason University participated in the study for course credit. Seven participants were excluded due to math task performance that fell below 90%. Of the 19 participants who were included in the behavioral analyses, 10 were included in the eye-tracking analysis.

Task and Materials

The major modification between this experiment and the last 2 experiments is the use of an auditory N-back as an interrupting task, instead of the multiple object tracking (MOT) paradigm.

Each interruption was composed of a 13-trial 2-back where participants were required to hold 2 letters in memory and indicate whether the third letter matched the number that was two back, i.e. does the third letter match the first, does the fourth letter match the second, etc. Participants were instructed that because no match was possible for the first two trials, they should indicate "non-match" for those. Participants indicated "match" and "non-match" using the left and right mouse buttons, respectively. Out of the 13 letters presented for each interruption, 3 were matches. These match occurrences were randomly distributed throughout the 13 trials. The duration of each auditory signal was 300 ms, with a 1-second response window and a 500 ms delay period between the end of the response window and start of the next trial. Participants were provided accuracy feedback for each response. Throughout the duration of the interruption, random visual noise played at approximately 10 Hz to discourage participants from staring at the pre-interruption location of the primary task.

Figure 16. Screenshot of the Quadrant task during an N-back interruption. The green border around the noise is the feedback indicator. This border was black at the start of each trial, green when a correct match or correct non-match was indicated, and red when an incorrect match or incorrect non-match was indicated.

Results

Post-Interruption Response Errors

No significant main effects of delay (*F(1,18)* = .147, $p < .706$), change (*F(1,18)* = .248, $p < .625$), or interactions (*F(1,18)* = .335, $p < .559$) were observed for post-interruption response errors across experimental conditions.

Resumption Lags

A significant effect of task location change was observed for resumption lags, where interruptions that changed the task location resulted in higher resumption lags than interruptions with no change in task location (*F(1,18)* = 7.728, $p < .012$, Figure 17).

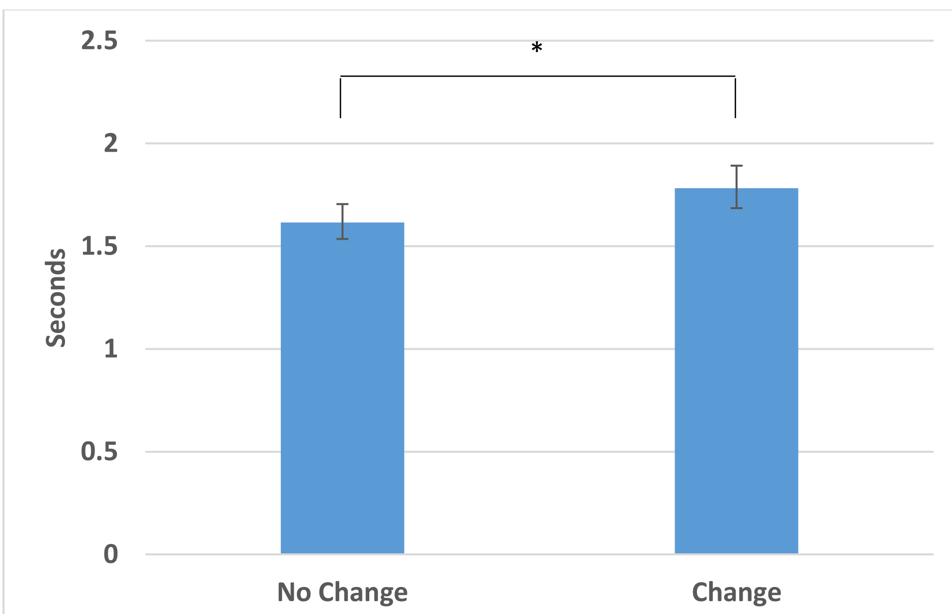

Figure 17. The effect of changes in task location following an interruption on resumption lags. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

Inter-Action Intervals

No significant main effects of delay (*F(1,17)* = 1.154, $p < .298$), change (*F(1,17)* = .447, $p < .513$), or interactions (*F(1,17)* = .516, $p < .482$) were observed for post-inter-action intervals across experimental conditions.

Post-Interruption Completion Times

Changing the location of the task post-interruption resulted in an increase in completion time over trials in which the task did not change location (*F(1,17)* = 12.110, $p < .003$, Figure 18), indicating that participants actually took longer to finish a column when the task changed location than when it did not.

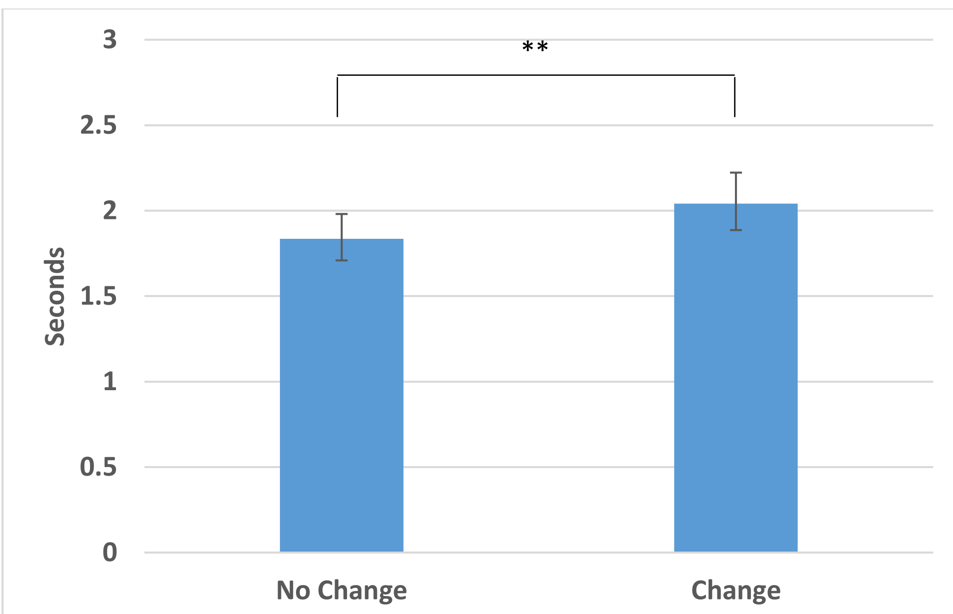

Figure 18. The effect of task location change on post-interruption object completion time. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

Eye-Tracking Data

As was the case in the previous experiments, both strict and liberal classification methodologies continue to point to participants exhibiting no preemptive eye-movements prior to task resumption. Similar to the results of Experiment 1, the analysis of the strict methodology revealed no significant difference between expected gaze behaviors and chance ($t(9) = 1.38$, $p < .201$, Figure 19), while the analysis of the liberal methodology revealed that expected gaze behaviors were significantly below chance ($t(9) = -.061$, $p < .953$, Figure 19).

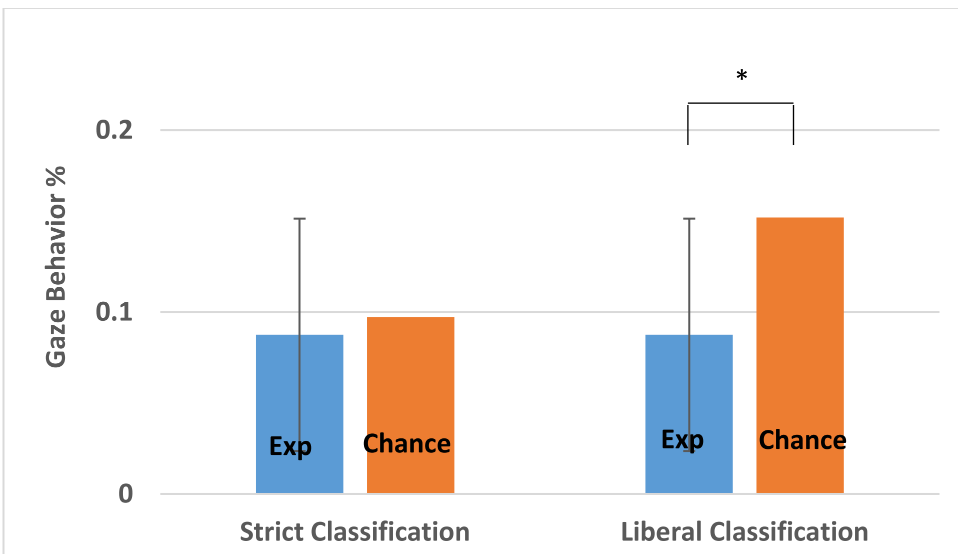

Figure 19. Comparison of gaze behaviors classified as expected gaze behaviors ("Exp") vs. computed chance values for strict and liberal classifications. Error bars are 95% CIs.

Discussion

Table 3. Results summary for Experiment 3.

Results Summary	
Measure	Exp. 3
Post-Interruption Errors	*NSF*
Resumption Lags	*No Change* < *Change*
Inter-Action Intervals	*NSF*
Post-Interruption Completion Times	*No Change* < *Change*
Gaze Behavior	For Strict: *Expected* = *Chance* For Liberal: *Expected* < *Chance*

Although the reappearance of the effects of change in the resumption lag and average completion time measures were good to see, there is only some consistency between either Experiment 1 or Experiment 2. Up to this point, we have established one highly consistent effect; the mounting evidence that participants show little to no evidence of anticipatory eye-movements towards the previous interruption location. Additionally, across Experiment 1, 2, and 3, post-interruption completion times have been affected in some manner; in Experiments 1 and 3, by changing the location of the primary task, and in Experiment 2, either due to the interruption trigger or whether a delay was present prior to interruption resumption.

Based on the combined results of the past three experiments up to this point, it appears that the effects of change, delay, and even interruption trigger are intermittent. As these effects are not consistent across the three experiments, it seems that evidence is mounting against the role memory for spatial location has in interruption resumption.

Experiment 4

Across these three experiments, we have seen that participants do not return their gaze to the last location where the primary task was displayed. It may be that participants are not even encoding the location of the task. Thus, Experiment 4 is designed to directly assess the explicit knowledge of the location of the primary task prior to an interruption. If participants are not able to report where the interrupting task was, this may explain why memory for spatial location is not leveraged in interruption resumption. If they are able to recall the expected location, something that was one of the previously-expressed possible explanations for the lack of "expected" gaze behaviors, then only the length of the delay window and/or hedging/poor location priming could explain participants' failure to return to the previous location.

Methods

Participants

Thirty-seven undergraduate students from George Mason University participated in the study for course credit. Nine participants were excluded due to math task performance that fell below 90%.

Task and Materials

The tasks and materials are identical to those discussed in Experiment 2, with the exception of a modification to the delay-no change condition. For all 8 interruptions under this condition, participants were given a question probe that asked them to select what quadrant the primary task was located in prior to the interruption. Participants were told during training this there was a possibility they would be asked about this, but were not exposed to it during the practice trials.

When the question probe appeared, it was accompanied by a rapid beeping, designed to encourage urgency in responding. The goal here was to discourage participants from thinking too hard about where the task was located. If participants did not respond in 5 seconds, the probe ended and participants were returned to the primary task.

No eye-tracking data were collected for this experiment.

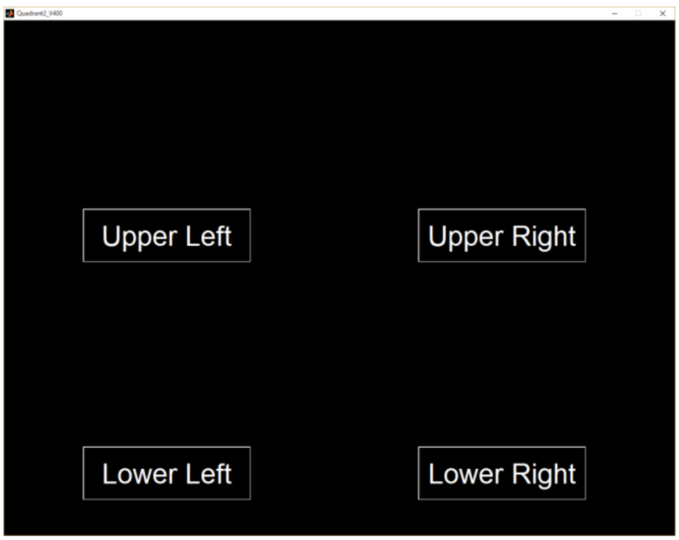

Figure 20. Picture of the Quadrant task when the question probe appears. Participants were required to click one of the four buttons to indicate to corresponding position as to where the primary task was originally located.

Results

Knowledge of Primary Task Location

This analysis was designed to determine whether participants could accurately report the location of the primary task prior to task resumption. A *t*-test confirmed that the correct responses of participants were significantly higher than the chance response rate ($t(27) = 5.360$, $p < .000$, Figure 21), indicating that participants do seem to have at least some memory for where the primary task was located prior to the interruption.

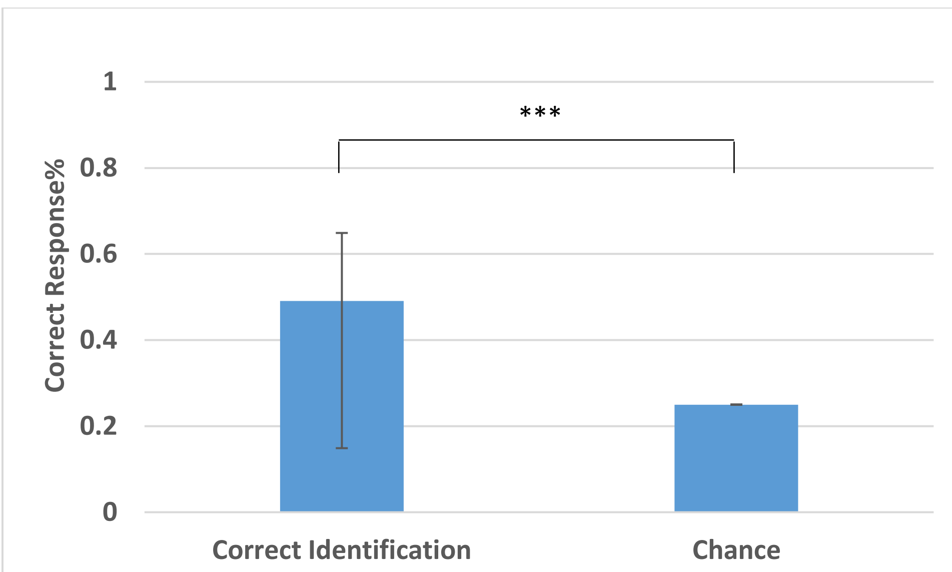

Figure 21. Mean correct primary task location responses of participants, compared against chance (25%). Error bars are 95% CIs.

Post-Interruption Response Errors

As was the case in previous experiments, this goal of this analysis was to assess the errors participants made following an interruption, and whether these errors were associated with changing the location of the primary task, or some other factor. The analysis of post-interruption errors in this experiment yielded a significant main effect of delay on errors ($F(1,27) = 4.720$, $p < .010$, Figure 22), with delay conditions resulting in a greater number of errors than no delay conditions. Further decomposing the locus of the post-interruption errors revealed that there were significant increases in the commission of both forgotten-carryover errors ($F(1,27) = 4.431$, $p < .039$) and unexplained errors ($F(1,27) = 4.431$, $p < .045$) between the no delay and delay conditions (Figure 23), with rates for both types of errors higher in the delay conditions than in the no delay conditions. The effect of delay on post-interruption response errors was something that had not been previously observed.

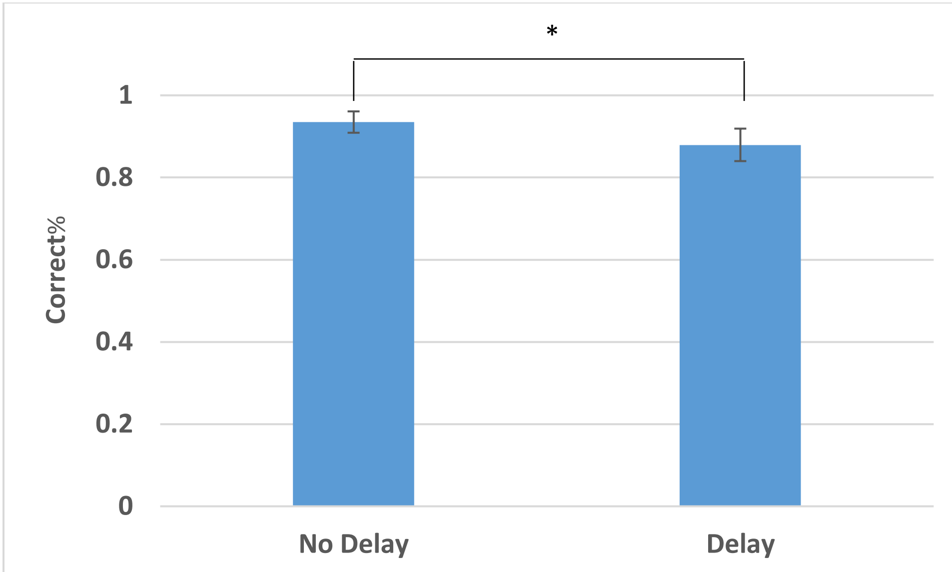

Figure 22. The effect of a delay prior to task resumption on the percentage of correctly-entered digits immediately following an interruption. Error bars are 95% CIs.

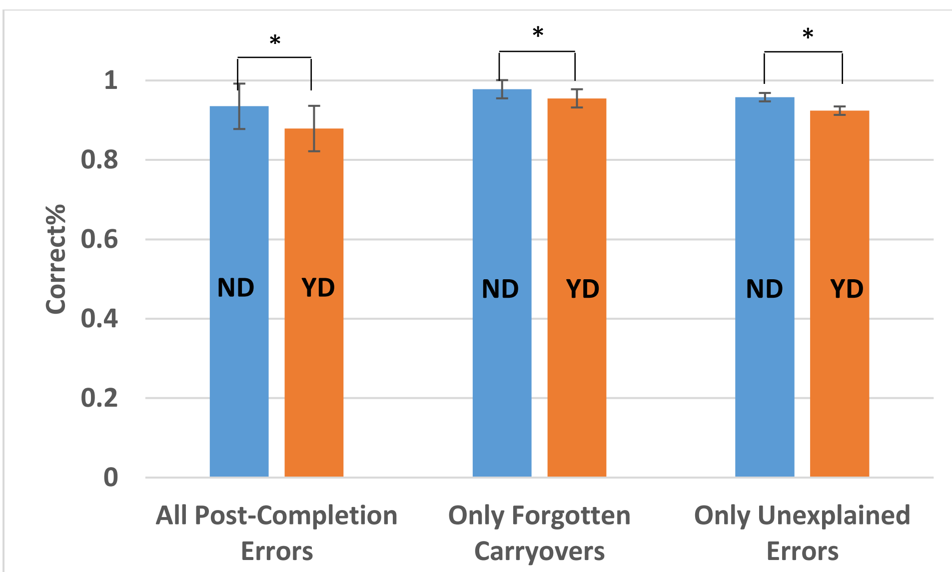

Figure 23. Percentage of correctly-entered digits immediately following an interruption between no delay (ND) and delay (YD) conditions account for all errors, only forgotten carryovers, and only unexplained errors. Error bars are 95% CIs.

Resumption Lags

No significant main effects of delay ($F(1,27) = 2.341$, $p < .138$), change ($F(1,27) = .101$, $p < .753$), or interactions ($F(1,27) = 3.013$, $p < .094$) were observed for resumption lags across experimental conditions.

Inter-Action Intervals

No significant main effects of delay ($F(1,23) = .160$, $p < .693$), change ($F(1,23) = 3.339$, $p < .081$), or interactions ($F(1,23) = 1.134$, $p < .298$) were observed for inter-action intervals across experimental conditions.

Post-Interruption Completion Times

There was only one significant effect that was observed with regard to post-interruption object completion times. As was the case in Experiment 1, a significant main effect of trigger was observed, with object completion times being significantly greater for time-triggered interruptions than for column-triggered ($F(1,23) = 14.619$, $p < .001$, Figure 24).

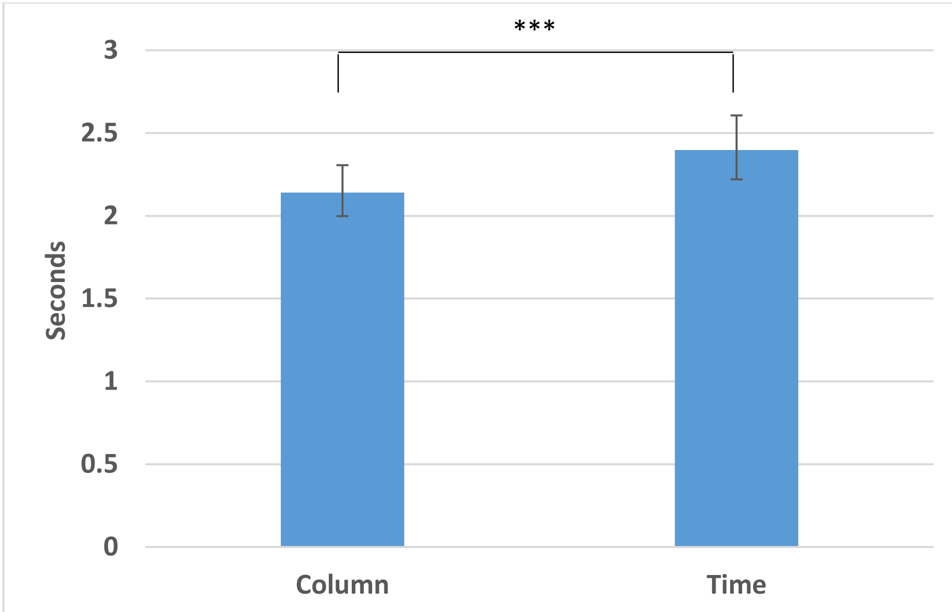

Figure 24. Average column completion times following column- and time-triggered interruptions. Error bars are 95% CIs. Displayed means and error bars are back-transformed values.

Discussion

Table 4. Results summary for Experiment 4.

Results Summary	
Measure	Exp. 4
Post-Interruption Errors	*No Delay < Delay*
Resumption Lags	*NSF*
Inter-Action Intervals	*NSF*
Post-Interruption Completion Times	*Column Trigger < Time Trigger*
Gaze Behavior	N/A

First, the performance data clearly suggest that participants do indeed have at least some idea of where the primary task was located prior to an interruption. This finding addresses any possibilities that the lack of significant expected gaze behaviors is due to participants not knowing where the task was located prior to the interruption.

Second, the results of the post-interruption response errors analysis in this experiment necessitate further examination. It is likely that the significant effect of delay on post-interruption response errors observed in this experiment is due to the addition of the question probe, which increased the total duration of the interruption and added an additional task that the participant needed to perform prior to resumption. This increased delay, while demonstrated in previous work to impact resumption lags (Monk, Trafton, &

Boehm-Davis, 2008), also appears to translate to the commission of both predictable and unexplained errors, at least in the context of this experiment.

Experiment 5

The first four experiments have demonstrated a lack of expected gaze behaviors and a clear answer to the question of whether participants know where the task was located prior to an interruption.

However, as it was previously noted, returning to the original task location may not always have been the most effective strategy in earlier studies. Because the task changed location as often as it remained in the same location when an interruption occurred, participants may have found that returning to the center of the screen was a better option than anticipating a return to a particular quadrant. With this in mind, Experiment 5 was designed to manipulate expectation of where the trial would resume by manipulating the number of trials that occurred in one location prior to an interruption occurring. When the pre-interruption location is consistent across a fairly high number of trials, are participants are more susceptible to interruption decrements than when the pre-interruption location is consistent across a lower number of trials? If the task changes location prior to resumption following 7 consecutive trials, task performance metrics like correct responses, completion times, and resumption lags will be negatively impacted, more so than if the task changes location prior to resumption following 3 trials. Additionally, if participants completed 7 consecutive trials prior to an interruption, gaze behaviors should reflect a greater likelihood to return to the pre-interruption location than if they completed 3 consecutive trials.

Methods

Participants

Twenty-seven undergraduate students from George Mason University participated in the study for course credit. Eight participants were excluded due to math task performance that fell below 90%. Of the 19 participants who were included in the behavioral analyses, 10 were included in the eye-tracking analysis.

Design and Procedure

The Quadrant task used in Experiment 5 was identical to the task used in Experiment 2, but with some modifications designed to test the hypothesis specific to this experiment. First, the no-delay condition was eliminated from this experiment, and following all interruptions, a delay of 1000 ms was implemented. Given the poor quality of 500 ms gaze data, it appeared participants were taking the opportunity to blink following the end of the interruption, eliminating a large portion of the data for that period. We hoped that increasing this window would allow for more expected gaze behaviors to be observed.

Second, the trials were organized into epochs to manipulate expectations of where the primary task would appear after an interruption. Within each epoch of trials, the task returned to the same location on all but the last trial of the epoch. On the last trial, the task either returned to the same location (no change) or moved to a new quadrant (change). Epochs were either short (3 trials total) or long (7 trials total), such that the longer sequence might set up a stronger expectation for where the task would appear following an interruption. The starting location appeared equally in all four quadrants. New epochs always started in a different quadrant than the previous epoch (Figure 25).

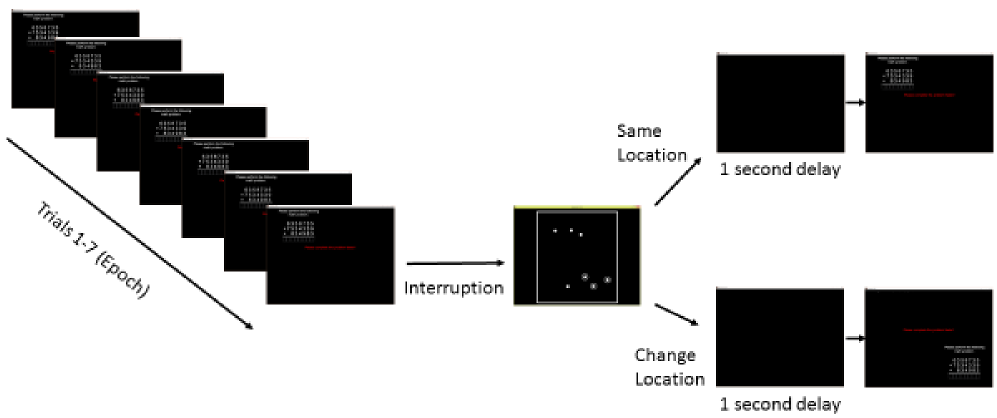

Figure 25. Breakdown of Experiment 5 for 7-trial sets.

Results

Post-Interruption Response Errors

No significant main effects of epoch ($F(1,18) = .321$, $p < .578$), change ($F(1,18) = .321$, $p < .578$), or interactions ($F(1,18) = .000$, $p < 1.000$) were observed for post-interruption response errors across experimental conditions.

Resumption Lags

No significant main effects of epoch (*F(1,18)* = .314, *p* < .582), change (*F(1,18)* = 1.131, *p* < .302), or interactions (*F(1,18)* = 1.362, *p* < .258) were observed for resumption lags across experimental conditions.

Inter-Action Intervals

No significant main effects of epoch (*F(1,18)* = .008, *p* < .930), change (*F(1,18)* = .074, *p* < .789), were observed for inter-action intervals across experimental conditions. A significant interaction of epoch and change was observed (*F(1,18)* = 6.752, *p* <.018), Figure 26, however, when decomposing the simple effects, no significant differences were observed.

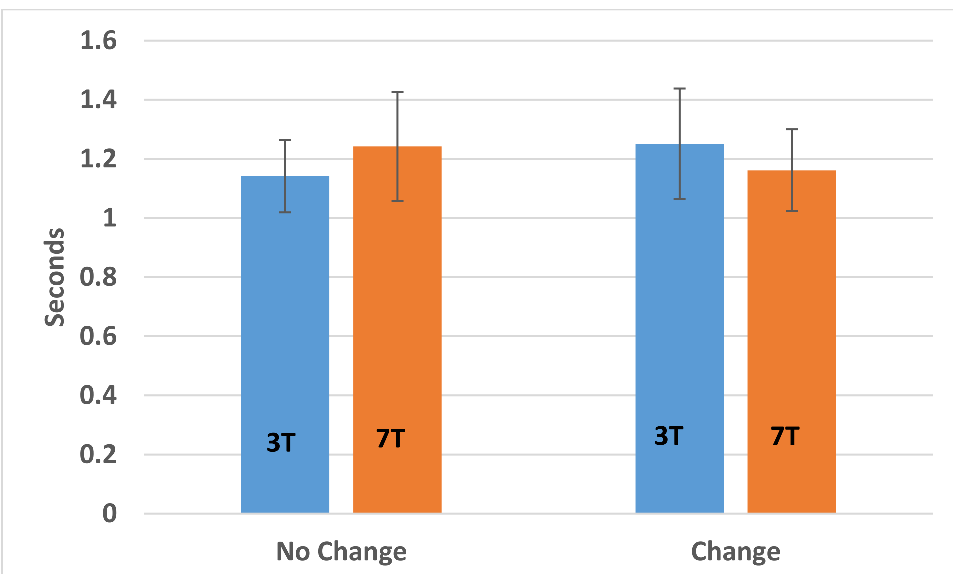

Figure 26. Comparison of inter-action intervals for 3-trial (“3T”) and 7-trial (“7T”) epochs across “no change” and “change” trials. Error bars are 95% CIs.

Post-Interruption Completion Times

A 2x2 Repeated Measures ANOVA was performed on the post-interruption completion times to examine the effects of epoch length and change. No significant main effect of epoch was observed ($F(1,18) = 1.007$, $p < .329$), but a marginal effect of change was ($F(1,18) = 4.480$, $p < .048$, *Figure 27*), with change resulting in slightly faster completion times, something that was unexpected. No significant change-by-epoch interaction was observed ($F(1,18) = 1.089$, $p < .311$).

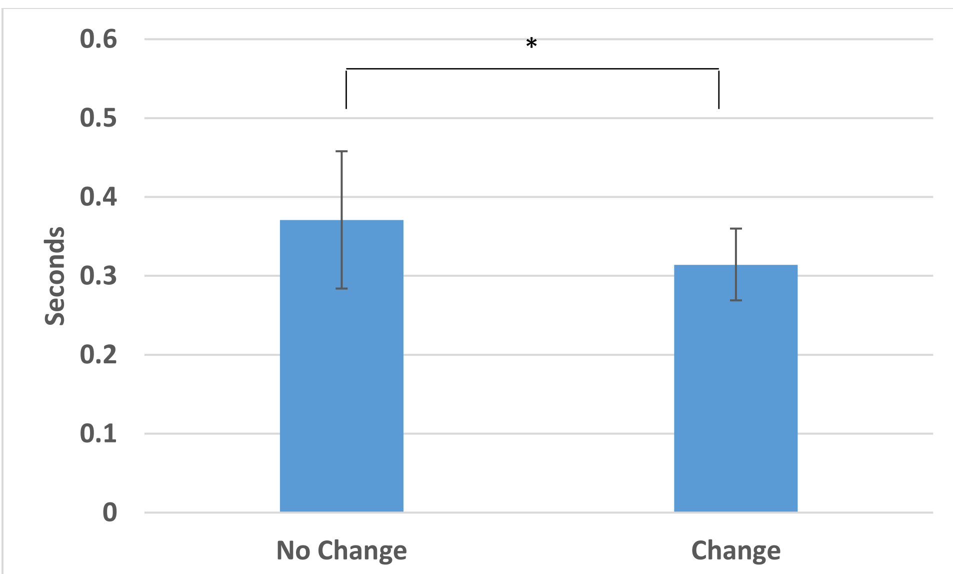

Figure 27. Comparison of the post-interruption completion times for “no change” and “change” trials. Error bars are 95% CIs.

Eye-Tracking Data

A one-way Repeated Measures ANOVA found no effect of epoch for either the strict (*F(1, 14)* = .651, p < .433) or liberal classification methodologies (*F(1, 14)* = .651, *p* < .433, Figure 28). In fact, in this experiment, the same number of events were successfully classified across both the strict and liberal methodologies.

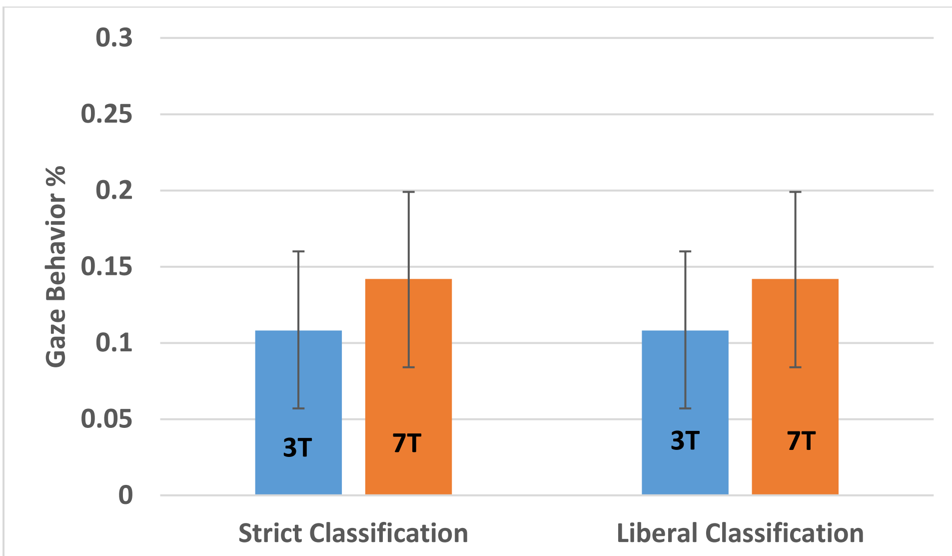

Figure 28. Comparison of gaze behaviors that were classified as expected in both 3-trial ("3T") and 7-trial ("7T") epochs using the strict and liberal methodologies, respectively. Error bars are 95% CIs.

Next, gaze behaviors that were classified as expected were compared against the chance values for both the strict and liberal methodologies using a one-sample *t*-test. For

3-trial epochs, expected gaze behaviors did not significantly differ from chance when using either the strict ($t(14) = .459$, $p < .653$) or liberal ($t(14) = -1.823$, $p < .09$) methodologies (Figure 29). Similarly, expected gaze behaviors for 7-trial epochs also did not differ using either the strict ($t(14) = 1.648$, $p < .122$) or liberal methodologies ($t(14) = -.386$, $p < .705$, Figure 30).

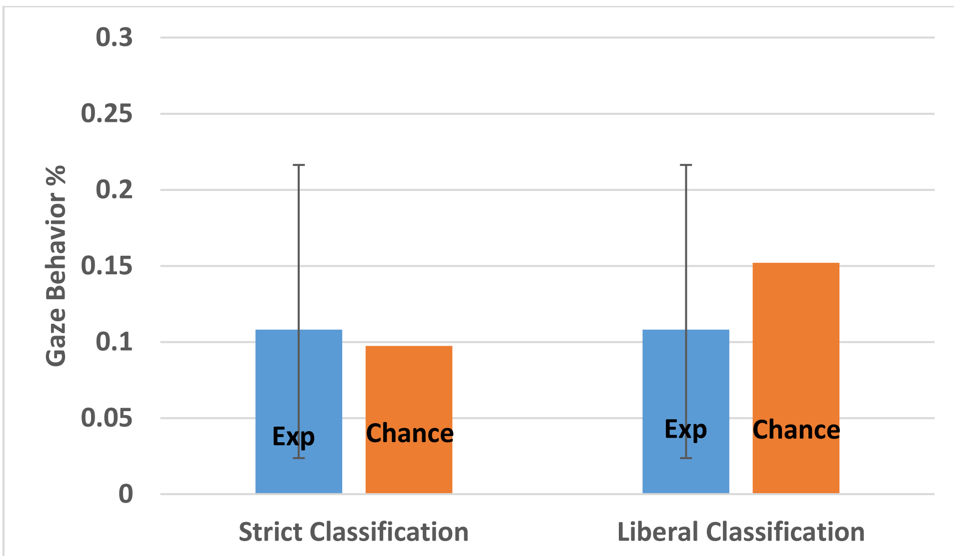

Figure 29. Breakdown of the percentage of gaze behaviors that were classified as expected gaze behaviors ("Exp") vs. computed chance values for strict and liberal classifications for 3-trial epochs. Error bars are 95% CIs.

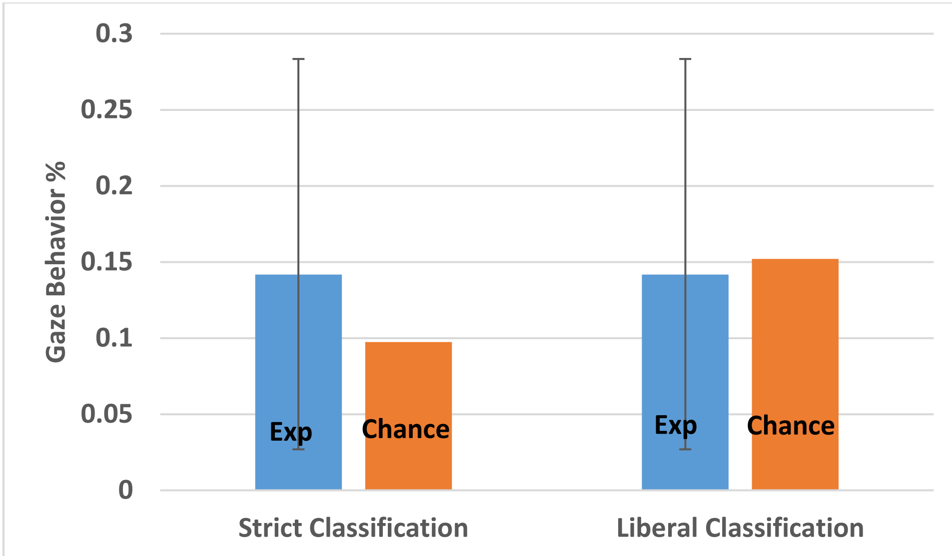

Figure 30. Breakdown of the percentage of gaze behaviors that were classified as expected gaze behaviors (“Exp”) vs. computed chance values for strict and liberal classifications for 7-trial epochs. Error bars are 95% CIs.

Discussion

Table 5. Results summary for Experiment 5.

Results Summary	
Measure	Exp. 5
Post-Interruption Errors	*NSF*
Resumption Lags	*NSF*
Inter-Action Intervals	*NSF*
Post-Interruption Completion Times	For 3-Trial Epochs: T1 > T2
Gaze Behavior	For 3-Trial Epochs: *Expected = Chance* For 7-Trial Epochs: *Expected = Chance*

The evidence continues to mount against spatial location playing a role in interruption resumption. This experiment demonstrates that even when multiple trials occur in the same location, the reinforcement of that location does little to improve post-interruption decrements, except in the case of post-interruption completion times, where there was a significant effect of trial for 3-epoch trials.

Furthermore, despite the increase in the delay period to allow for more intact gaze data to be collected, as well as a reduction of the number of interruptions, expected gaze movements were still classified far less frequently than unexpected movements, suggesting that there seems to be no motivation on the part of the participant to preempt interruption return. If memory for spatial location does play a role in interruption resumption, it seems that it is unaffected by the number of uninterrupted trials that occur in a given location prior to an interruption.

Experiment 6

Experiment 5 showed that the ability to resume after an interruption is not affected by how frequently a task occurs in one location prior to it changing location. However, what if the task always resumed in a particular location? Would interruption resumption improve if participants could consistently anticipate where the task would appear after an interruption? Experiment 6 is designed to test this scenario by using an experimental trial structure that helps participants implicitly learn where the primary task will resume following an interruption. If memory for spatial location can be strengthened through implicit learning of where the primary task will always resume, improved resumption performance should be observed. As participants complete interruptions with resumptions that return the task to a consistent location, task performance metrics like correct responses, completion times, and resumption lags improve. Additionally, as participants are exposed to these predictable resumption locations, gaze behaviors should reflect a greater likelihood to return to this location following an interruption.

Methods

Participants

Twenty-seven undergraduate students from George Mason University participated in the study for course credit. Seven participants were excluded due to math task performance that fell below 90%. Of the 20 participants who were included in the behavioral analyses, 16 were included in the eye-tracking analysis.

Design and Procedure

The task used in Experiment 6 was identical to the task used in Experiment 2, modified to test the hypothesis specific to this experiment. Like Experiment 5, the no-delay condition was eliminated from this experiment, and following all interruptions, a delay of 1000 ms was implemented.

Conceptually, the trial structure for Experiment 6 is based on the idea of a "protected quadrant," where the primary task will only resume following an interruption. For example, if a participant was supposed to learn that the upper left quadrant of the screen was where the task would always resume following an interruption, no trial would ever start there, and following every interruption, the task would always resume there. However, participants could not be exposed to interrupted trial after interrupted trial, as such a paradigm would likely hurt generalizability between previous experiments (which all had interruption rates between 20-30%) and would likely lead to task fatigue.

As a result, Experiment 6 used four blocks of seven epochs of trials, which allowed us to maintain an interruption-type design. Each epoch was comprised of three trials, two that were uninterrupted trials that would occur in any location other than the protected quadrant, and a third interrupted trial. This trial would start in a location other than the protected quadrant, but following the interruption, would resume in the protected quadrant. For example, if the upper right quadrant (Q2) is considered the protected quadrant, the first trial might occur in the upper left quadrant (Q1), the second trial might occur in the bottom right quadrant (Q3), and the third trial might start in the bottom left quadrant (Q4). Once the third trial is interrupted, the participant is asked to complete a MOT trial, and following a 1000 ms delay, will then resume the primary task in the protected quadrant (Figure 31).

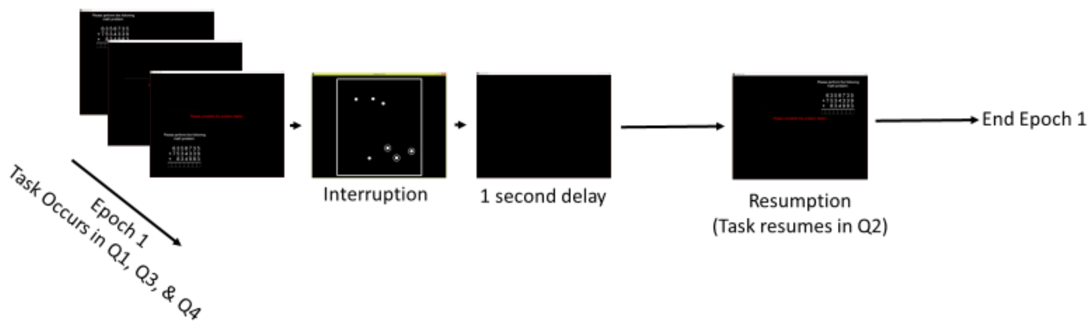

Figure 31. Breakdown of an epoch for Experiment 6. In this example, the second quadrant (Q2) is considered the protected quadrant.

Results

Eye-Tracking Data

The goal of this analysis was to determine whether participants learned to look at the protected quadrant (where the task resumes) over time. To assess this, expected gaze behaviors were first averaged across block and compared across each of the 7 epochs using a one-way Repeated Measures ANOVA for each gaze classification methodology.

Both ANOVAs resulted in no significant main effects of trial for either the strict (*F(6, 84)* = .538, p < .778) or liberal methodology (*F(6, 84)* = .538, p < .778), echoing previous findings that participants show no evidence for looking at the expected task location prior to resumption.

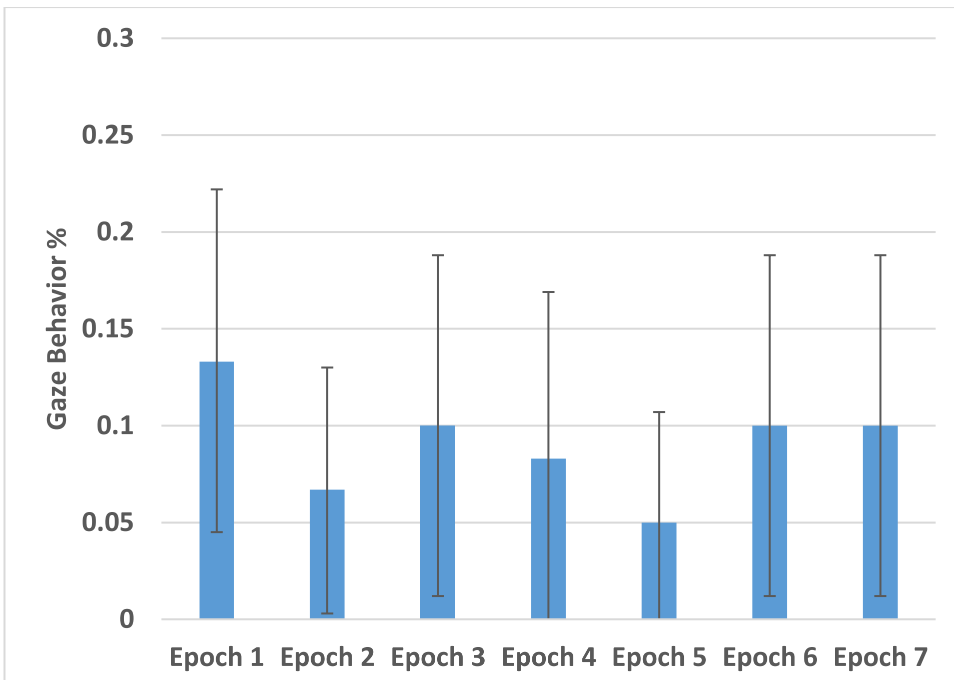

Figure 32. Breakdown of the percentage of gaze behaviors that were classified as expected gaze behaviors across all blocks for each of the 7 interruptions. The values shown are for the strict classification methodology, but are identical to the liberal classification methodology. Error bars are 95% CIs.

Next, gaze behaviors that were classified as expected were averaged across block and compared against the chance values for both the strict and liberal methodologies using a one-sample *t*-test for each of the 7 epochs. In the case of the strict methodology, none of the expected gaze behaviors differed significantly from chance (Figure 33). With regard to the liberal methodology, only the second ($t(14) = -2.890$, $p < .012$) and fifth epochs ($t(14) = -3.819$, $p < .002$) differed from chance, with classified percentages that fell below chance (Figure 34).

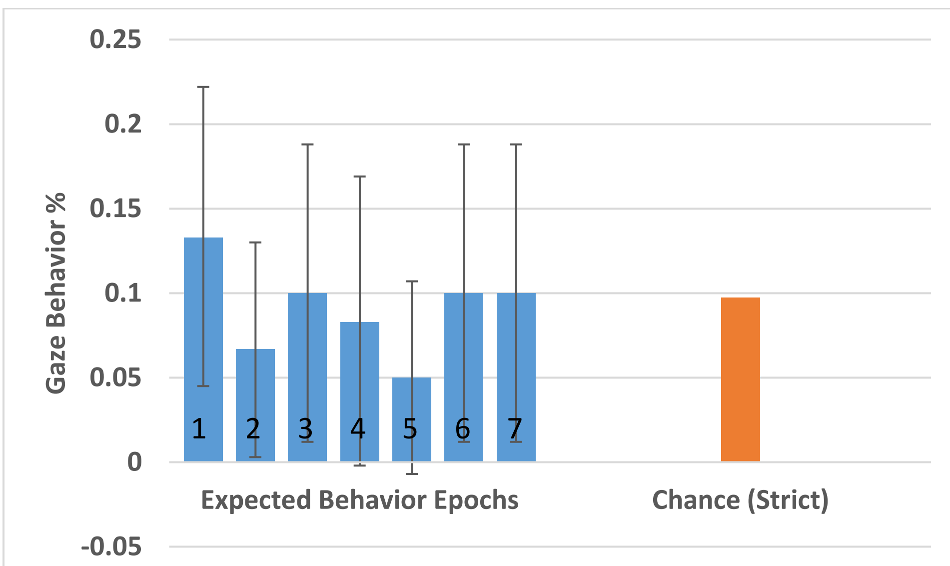

Figure 33. Comparison of all epochs (1-7) against the chance value for the strict classification methodology. Error bars are 95% CIs.

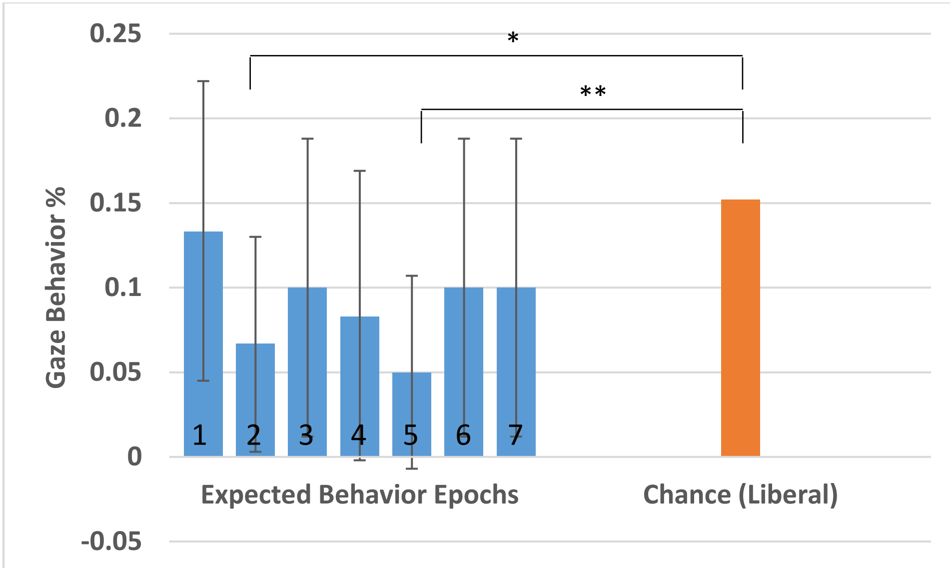

Figure 34. Comparison of all epochs (1-7) against the chance value for the liberal classification methodology. Error bars are 95% CIs.

Post-Interruption Response Errors

Post-interruption errors were analyzed using a 4x7 Repeated Measures ANOVA to examine the effects of each block (equating to each of the four quadrants) and interrupted trial (equating to each of the interrupted trials in the 7 epochs). This analysis yielded no significant main effects of block ($F(3, 57)$ = .967, $p < .415$) or trial $F(6, 114)$ = 1.257, $p < .298$), or a block-by-trial interaction ($F(18, 342)$ = .771, $p < .734$).

Resumption Lags

Resumption lags were analyzed using the same 4x7 Repeated Measures ANOVA procedure, and no significant main effects of block ($F(3, 57)$ = .917, $p < .439$) or trial

$F(6, 114) = 1.353$, $p < .240$) or a significant block-by-trial interaction ($F(18, 342) = 1.265$, $p < .208$) were observed.

Inter-Action Intervals

No significant main effects of block ($F(3,57) = .576$, $p < .633$), trial ($F(6,114) = 1.697$, $p < .128$), or interactions ($F(18,342) = .783$, $p < .721$) were observed for inter-action intervals across experimental conditions.

Post-Interruption Completion Times

No significant main effects of block ($F(3,57) = .357$, $p < .784$ trial ($F(6,114) = 1.259$, $p < .282$), or interactions ($F(18,342) = 1.015$, $p < .442$) were post-interruption completion times across experimental conditions.

Discussion

Table 6. Results summary for Experiment 6.

Results Summary	
Measure	Exp. 6
Post-Interruption Errors	*NSF*
Resumption Lags	*NSF*
Inter-Action Intervals	*NSF*
Post-Interruption Completion Times	*NSF*
Gaze Behavior	*Epochs ≈ Chance*

The results of this experiment suggest that, even if participants are exposed to the resumption of a task in a consistent location, they are unable to leverage that predictability to improve post-interruption performance, as we saw no effects of epoch in any measures of task performance. Furthermore, the results of the gaze analyses continue the same trend as previous experiments; participants show no evidence of anticipating the interrupting task in the expected quadrant. At this point, concerns about the lack of expected gaze behaviors caused by the length of the delay window, stronger and more consistent priming of the resumption location, task interface design, and participants' knowledge of pre-interruption task locations have all been addressed.

For Experiments 5 and 6, participants were not explicitly briefed on the trial structure. Participants were trained exactly as they had been for Experiments 1 and 2. Specifically, that they would be performing some math problems, and occasionally, in performing those math problems, they could be interrupted. It is possible that explicit instructions may have resulted in the learning we hoped to see for Experiments 5 and 6, as perhaps the patterns were too subtle to be noticed by participants. However, it should be noted that we intentionally opted against explicit instructions because we believed that memory for spatial was an implicit process, and because real-world interruptions do not operate under a constrained or predictable set of circumstances.

General Discussion

The goal of this work was to establish the role that memory for spatial location plays in interruption resumption, something manipulated by changing the location of the primary task prior to resumption. The effects of this manipulation were not consistent.

Table 7. Summary table for all 6 experiments. "+" cells represent 1 or more effects that supported one or more hypotheses, "-" cells represent cases where all observed effects did not support any hypotheses, and "=" cells represent cases in which no significant effects were observed.

Results Summary						
Measure	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6
Post-Interruption Errors	+	=	=	-	=	=
Resumption Lags	+	=	+	=	=	=
Inter-Action Intervals	+	=	=	=	=	=
Post-Interruption Completion Times	+	+	+	+	=	=
Gaze Behavior	-	-	-	N/A	-	-

Our first hypothesis, that when a primary task changes from one location to another following an interruption, was partially supported. Negative impacts of change were observed in Experiments 1 and 3. In the case of Experiment 1, effects on post-interruption errors, resumption lags, and post-interruption completion times were observed. With regard to Experiment 3, effects of change on resumption lags and post-interruption completion times were observed. The inconsistency of effects here certainly necessitates more investigation.

Our second hypothesis, that participants will leverage any memory for spatial location by saccading to, or fixating near, the pre-interruption location, does not appear to be supported. Although there is certainly room to continue to refine our classification algorithms and constrain the experiment in order to improve acquisition integrity, a 500-1000 millisecond window should be a long enough time to capture any participant saccades, should there be any. However, the number of expected eye-movements we classified were quite low, despite the fact that participants do seem to be able to recall the original primary task location, discounting the possibility that participants do not saccade to the appropriate location because they cannot remember it. Although Ratwani & Trafton (2008) did find that participants return to the previous location following an interruption, we found no evidence of this.

As was discussed after Experiment 1, we raised a number of possibilities for why no preemptive eye-movements were observed. Through virtually each experiment, we attempted to systematically eliminate those possibilities. Experiment 2 eliminated the task dividers (crosshairs) that could potentially contribute to participants staring at the center of the screen. Experiment 4 was explicitly designed to test our third hypothesis, that that participants were able to recall where the task was located prior to interruption, a hypothesis that does appear to be supported by the response rates that were above chance.

However, in Experiments 5 and 6, not only was the window in which a critical event could occur increased, which was another concern, but the value of looking at the previous location was greatly increased compared to Experiments 1-4. Through the implementation of pre-interruption and post-interruption location strengthening for Experiments 5 and 6, respectively, we sought to test two different hypotheses. First, in Experiment 5, we sought to test our fourth hypothesis that pre-interruption location strengthening would result in greater interruption decrements when the primary task changed location. This was not supported by the results of Experiment 5. In Experiment 6, we sought to test our fifth hypothesis, that post-interruption location strengthening would result in improved interruption resumption performance. Again, no support for this was observed.

It’s important to note that in Experiment 6, the value of returning to the primed location, which in this experiment was the protected quadrant, was at its highest. Once a new protected quadrant was established, participants should have been able to anticipate the return location of the next six interruptions. However, despite addressing all of these design concerns, participants still did not return to the previous location.

Perhaps one of the only ways to further increase the value, so to speak, of returning to the primary task’s pre-interruption location, would be through the implementation of a gaze-contingent paradigm, where during delay conditions, the primary task would not resume until participants shifted their gaze towards the last known location of the primary task. Using such a design might explicitly emphasize preemptive eye-movements, something that was not done in this study, and aid in interruption resumption.

Finally, we stated two auxiliary hypotheses in this work that centered around the nature of interruptions in general. First, we hypothesized that participants who were interrupted just after completing a column would show attenuated interruption decrements compared to those who were working within a column. This hypothesis appears to be supported, as any significant effects of trigger that were observed through analyses showed almost complete consensus that column-triggered interruptions resulted in better performance than time-triggered interruptions. The second hypothesis was that any effects of change or delay, particularly those with regard to change, would be agnostic to the interrupting task. The significant effects of change observed in Experiment 3, where interruptions differed than any of the other experiments, do support the fact that regardless of the interrupting task, change effects can be observed. However, given how varied the results are between experiments, certainly more work must be done in this area prior to definitively stating whether this truly is or is not the case.

Overall, these data allow us to speak to the extent to which memory for spatial location plays in interruption resumption. Although previous research found that spatial memory for location does play a role in interruption, our results were less consistent. In some experiments, the effects of task location change resulted in marked decreases in performance, while in other experiments, no effects of change were observed.

Additionally, through all six experiments, we observed very little evidence that participants ever returned to the previous location of the primary task following an interruption but prior to resumption. Finally, even when attempted to leverage spatial memory through strengthening either pre- or post-interruption strengthening, no performance decrements or improvements were observed.

Caveats

Overall, this work has illustrated that the role that memory for spatial location plays in interruption resumption is small, if at all existent. Despite changing the resumption location, performance proved to be relatively unaffected whether the task changed location, with only some exceptions. Furthermore, while previous research demonstrated that participants did return to where they were (Ratwani & Trafton, 2006), we observed no evidence of this, even when participants could anticipate the resumption location.

There are some limitations that should be addressed, should further replications take place. For starters, the column- and time-trigger option should be constrained, such that only one trigger option is used. This feature, while initially implemented to make the task more unpredictable, and hence realistic, ultimately complicated matters and likely introduced too much variability in the design. Additionally, the significant effect of delay due to the implementation of the question probe in Experiment 4 underscores that even a few extra seconds could drastically increase the negative effects of an interruption. Perhaps with shorter interruptions, the effects of change would be more consistent than in this work. Finally, Experiments 5 and 6 relied solely on implicit learning; participants were not given any up-front instructions as to how the task would operate. Future manipulations may consider implementing instructions that more clearly convey the underlying behavior of the paradigm, which may allow participants to better leverage any memory for spatial location, should such a process take place.

Finally, we had initially hoped that this dissertation would inform Long-Term Working Memory (LTWM), Threaded Cognition, and Memory for Goals and the role spatial memory might play in each. Unfortunately, the results of this work do not provide any new insight on any of these theories.

Appendix A

Gaze Classification Algorithm. For this analysis, only trials in which a delay occurred were used. This is because we wanted to see where the eyes move following an interruption, but prior to the task returning. For these trials, the gaze classification algorithm established an analysis window that used only raw gaze data that occurred between 750 ms prior to the delay period (effectively the end of the interruption period) and 83 ms following the delay period (effectively the beginning of the resumption period). The beginning of this analysis window was selected to ensure that the algorithm had the opportunity to identify any preemptive saccades or fixations that occurred as participants made their final response to the interrupting task. Of course, it should be noted that using this data has the potential to introduce additional noise, and as such, any classified events that occurred during the end of the interruption period were treated with less confidence than classified events that occurred during the delay period.

The end of this analysis window was selected so that the algorithm had the opportunity to identify any saccades or fixations that may have been initiated at the end of the delay period but would not have been classified due to the partitioning of gaze data between the delay and resumption period. If a saccade or fixation was present within the window, the algorithm would select the last event (referred to after this point as the critical event) that occurred in the analysis window.

If a fixation was selected as the critical event (CE), two distances were computed from it: from the center of the screen and from the middle of the quadrant where the task previously occurred. The first distance was used to ensure that participants were not just staring at the center of the screen. Any CE that was within 100 pixels from the center of the task window (i.e. the crosshair in Experiment 1) was categorized as such (CE1 in Figure 35). If the CE was greater than 100 pixels away from the center, the second computed distance was used to determine if participants were fixating relatively closely to the task location. A CE location less than 200 pixels from the center of the task location (CE3 in Figure 35) was determined to have a “very close distance;” a location less than 250 pixels away (CE2 in Figure 35) was considered to have a “close distance.” Any greater distance was determined to be “not close.”

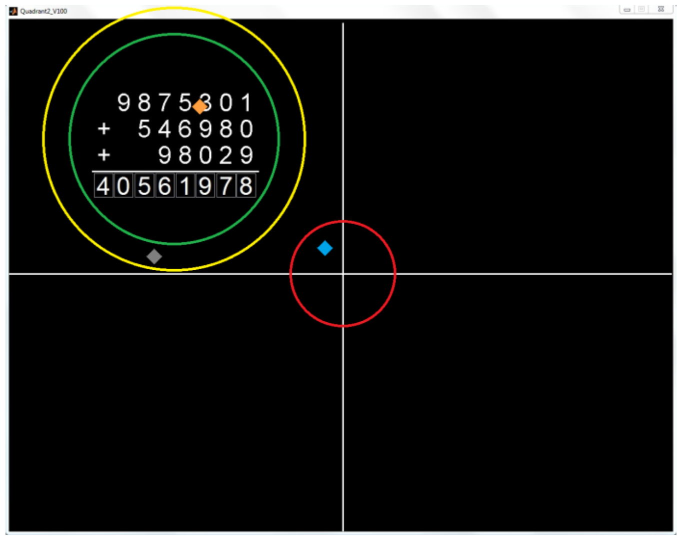

Figure 35. Screen capture of the Quadrant task demonstrating 3 fixations that occur within different classification regions. CE1, CE2, and CE3 are represented by the blue, gray, and orange diamonds, respectively. The red circle illustrates a region where fixations would not be counted. The yellow circle and green circles represent the “close” and “very close” regions for a given trial around where the primary task was previously located.

If a saccade was selected as the CE, a similar distance determination was made. As was the case with fixations, any saccade that ended within 100 pixels from the center of the task window was also classified as “not close” (CE4). If the last gaze point of the CE was less than 200 (CE6), less than 250 (CE5), or greater than 250 pixels away from the center of where the task was previously location, then the CE was determined “very close,” “close,” or “not close,” respectively (Figure 36).

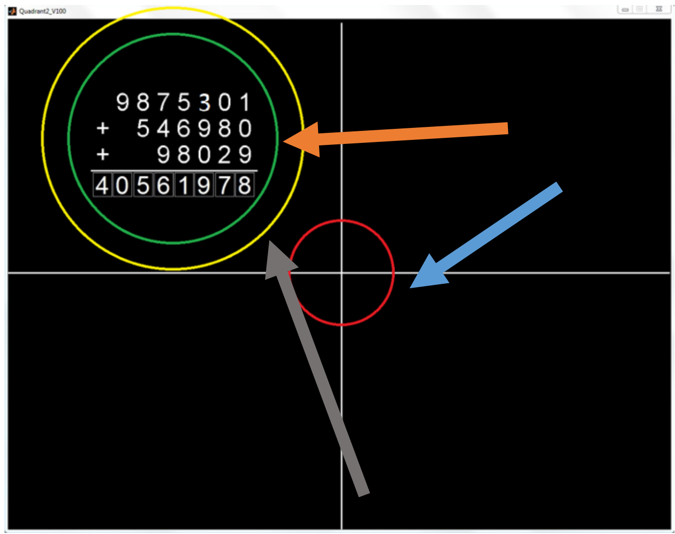

Figure 36. Screen capture of the Quadrant task demonstrating 3 saccade vectors that end in different classification regions. CE4, CE5, and CE6 are represented by the blue, gray, and orange arrows, respectively.

Once a distance determination was made, a final event classification was made by considering the reliability of the data. Recall that the event selected could come from ether the delay period or the interruption period. Events that were classified during the delay period were much closer to the resumption of the task, and as such, were likely much more representative of an overt shift in anticipation of the task returning. As you get further away from that time point, that assumption becomes more tenuous, so the event classification decision must account for this. Thus, there are 5 levels in the final decision; “almost certainly,” “highly likely,” “likely,” “questionable,” and “not likely.” There are 2 additional levels reserved for situations where a decision could not be reached, such as when a CE occurred within 100 pixels from the center of the task, or if no CE could be identified for a trial due to bad data (see Table 8 for more information on how the final decision is reached).

Table 8. Detailed breakdown of how the distance and direction determinations for critical events (CEs) are classified into different levels of the final decision.

Critical Event Classification Level Details

Level	Description
5	Delay period CEs that are within optimal distance
4	Delay period CEs that are within the expanded distance
3	Interruption period CEs within optimal distance
2	Interruption period CEs within the expanded distance
1	Any CE outside of the expanded distance
0A	Participant stared at the center of the screen
0B	No CE could be identified

Once a final decision was reached, the results were binned into either an expected or unexpected category, where expected behaviors are CEs that exhibited a classifiable movement back towards the previous task location prior to it appearing, and unexpected behaviors are CEs that exhibited either no classifiable movement towards or a classifiable movement away from the previous task location. Using the strict classification methodology, only the top three levels (5, 4, and 3) were counted as expected movements. Using the liberal classification methodology, Level 2, was also included as an expected movement.

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Biography

William Miller received his Bachelor’s degree in Psychology from the University of Dayton in 2010. After receiving a Science, Mathematics, and Research for Transformation (SMART) fellowship from the Department of Defense, he was accepted to George Mason University, where he received his Masters of Arts in Psychology in 2012, and then his Doctorate in Psychology with a concentration in Human Factors and Applied Cognition in 2017.