# An Eye Movement Analysis of the Effect of Interruption Modality on Primary Task Resumption

**Raj Ratwani,** George Mason University, Fairfax, Virginia, and **J. Gregory Trafton,** Naval Research Laboratory, Washington, DC

**Objective:** We examined the effect of interruption modality (visual or auditory) on primary task (visual) resumption to determine which modality was the least disruptive.

**Background:** Theories examining interruption modality have focused on specific periods of the interruption timeline. Preemption theory has focused on the switch from the primary task to the interrupting task. Multiple resource theory has focused on interrupting tasks that are to be performed concurrently with the primary task. Our focus was on examining how interruption modality influences task resumption. We leverage the memory-for-goals theory, which suggests that maintaining an associative link between environmental cues and the suspended primary task goal is important for resumption.

**Method:** Three interruption modality conditions were examined: auditory interruption with the primary task visible, auditory interruption with a blank screen occluding the primary task, and a visual interruption occluding the primary task. Reaction time and eye movement data were collected.

**Results:** The auditory condition with the primary task visible was the least disruptive. Eye movement data suggest that participants in this condition were actively maintaining an associative link between relevant environmental cues on the primary task interface and the suspended primary task goal during the interruption.

**Conclusion:** These data suggest that maintaining cue association is the important factor for reducing the disruptiveness of interruptions, not interruption modality.

**Application:** Interruption-prone computing environments should be designed to allow for the user to have access to relevant primary task cues during an interruption to minimize disruptiveness.

**Keywords:** human-computer interaction (HCI), eye tracking, multiple resources, attentional processes, interruption modality, task resumption

Address correspondence to Raj Ratwani, 4400 University Drive, MS3F5, Fairfax, VA 22030; rratwani@gmu.edu.

*HUMAN FACTORS*
Vol. 52, No. 3, June 2010, pp. 370–380.
DOI: 10.1177/0018720810374195.

## INTRODUCTION

The frequency and disruptiveness of interruptions has been well documented (Gonzalez & Mark, 2004; Hodgetts & Jones, 2006a, 2006b; Monk, Boehm-Davis, & Trafton, 2004), yet interruptions are part of everyday life and are often unavoidable. The ubiquity of interruptions has led researchers to examine ways of reducing the costs of interruptions. Methods of interruption management include presenting explicit cues upon resumption of the primary task (Trafton, Altmann, & Brock, 2005), rehearsing the primary task goal (Trafton, Altmann, Brock, & Mintz, 2003), delivering interruptions at specific points in the primary task (Bailey & Iqbal, 2008), and providing interruption notifications (McFarlane, 2002).

Interruption modality has been examined as a possible method of interruption management as well. There are several theoretical explanations for the effect of interruption modality on performance; however, the theories tend to focus on distinct periods of the interruption paradigm. The interruption paradigm has been described as consisting of three distinct periods (Trafton et al., 2003; Wickens & McCarley, 2008). First, an operator must switch from the primary task to the interrupting task (called Switch 1 or the interruption lag). Next, the operator performs the interrupting task, either concurrently with the primary task, or a more complete attentional shift to the interrupting task may be required. Finally, the operator switches from the interrupting task back to the primary task (called Switch 2 or the resumption lag).

Preemption theory has focused on processes at Switch 1 and suggests that information presented via the auditory channel has greater attention-capturing properties compared with the visual channel (Spence, 2001). Thus, an auditory interruption will more immediately capture the attention of the user and will result in better performance on the interrupting task as compared with a visual interruption, regardless of the modality of the primary task. However, because of the immediate attention capture from the auditory interruption, there may be a detriment to performance on the primary task (Wickens & Colcombe, 2007). Empirically, there has been mixed support for auditory preemption theory. Several studies have found that people do in fact respond more quickly to auditory interruptions with a detriment to the primary or ongoing task (Helleberg & Wickens, 2002; Latorella, 1998; Wickens & Liu, 1988; Wickens, Dixon, & Seppelt, 2005), whereas other studies have found no detriment to the ongoing task (Helleberg, Wickens, & Goh, 2003; Iani & Wickens, 2007).

Multiple resource theory (Wickens, 1984, 2002), which was originally formulated to explain performance in dual-task (Hazeltine & Ruthruff, 2006) and time-sharing paradigms (Horrey & Wickens, 2004; Liu & Wickens, 1992; Sarno & Wickens, 1995), suggests that visual and auditory perception rely on different pools of fixed resources (Wickens, 2008). Researchers (Ho, Nikolic, & Sarter, 2001; Ho, Nickolic, Waters, & Sarter, 2004; Latorella, 1998) have extended multiple resource theory to the interruptions paradigm, specifically to account for processes when the interrupting task is to be performed concurrently with the primary task.

Under concurrent interrupting and primary task performance conditions, multiple resource theory would suggest that an interruption presented in a different modality from the primary task (i.e., cross-modal) should be less disruptive than an interruption presented in the same modality as the primary task (i.e., intramodal). In the cross-modal case, the primary and interrupting tasks rely on different pools of resources; consequently, the primary task should incur less disruption than the intramodal case, in which the tasks share the same pool of resources.

Within an interruptions paradigm, empirical results have mostly been in support of the cross-modal benefit suggested by multiple resource theory. Latorella (1998) found that error rates were higher on an auditory primary task with auditory interruptions, supporting multiple resource theory. Ho et al. (2001) found that visual interruptions led to the largest number of errors on a visual primary task, whereas auditory interruptions led to the least amount of interference. Furthermore, when participants performed a visual primary task with advanced knowledge of the modality of an imminent interruption, there was a preference to delay visual interruptions longer than auditory interruptions (Ho et al., 2004); visual interruptions were likely postponed to avoid intramodal conflict.

A third theory that has been applied to the interruptions paradigm and has accounted for several empirical findings (Hodgetts & Jones, 2006a, 2006b; Monk et al., 2004; Monk, Trafton, & Boehm-Davis, 2008) is an activation-based theory of goal memory, called memory for goals (Altmann & Trafton, 2002, 2007). Memory for goals suggests that the current most active goal directs behavior and that the activation levels of goals decay over time. When interrupted, the current primary task goal is suspended, and the activation level of the suspended goal decays. Upon resumption, the time required to begin work on the primary task reflects the process of retrieving the suspended goal. The higher the activation level of the suspended goal, the more easily that goal can be retrieved. Activation levels are determined by two constraints: strengthening and priming. The strengthening constraint suggests that the history of the goal (i.e., frequency or recency of goal retrieval) affects goal activation. The priming constraint suggests that cues in the environmental or mental context provide associative activation or priming to the associated goal in the primary task and thus facilitates retrieval.

Our goal in this study was to examine how the modality of the interrupting task influences resumption of the primary task (Switch 2), specifically when the primary task does not have explicit concurrent task demands with the interrupting task. Preemption theory is focused on Switch 1 and does not make predictions about resumption of the primary task. Multiple resource theory is more focused on interruption paradigms that have concurrent interruption and primary task demands.

Memory for goals does not make explicit predictions about the effect of interruption modality on resumption, but the priming constraint can be leveraged to make predictions about how detrimental an interruption modality will be to the resumption of the primary task (Switch 2). Specifically, an interruption that allows for the associative link between environmental cues and the target goal to be maintained during the interruption should lead to less disruption during Switch 2. Thus, the interruption modality that allows for this associative link to be maintained will be less disruptive than modalities that do not allow for this associative link. In this study, we sought to directly test this prediction by focusing on eye movements during the interruption and during resumption of the primary task.

## EXPERIMENT

The primary task was a computer-based visual task with a hierarchical goal structure. There were two different interruption modalities (auditory, visual) that were manipulated across three different conditions. In the auditory-visible condition, an auditory interruption was presented while the primary task interface was still completely visible to the participant. In the auditory-blank condition, an auditory interruption was presented, but a blank screen occluded the primary task interface. In the visual condition, a visual interruption was presented that occluded the primary task interface. In the auditory interruption conditions, during the interruption, one could continue to fixate on the point where the primary task was left off. In the visual interruption condition, it was not possible to continually fixate on this point. When returning to the primary task after the interruption, participants had to remember what specific subgoal was being worked on and had to return to the spatial location on the interface associated with the to-be-resumed subgoal.

### Theoretical Predictions

Memory for goals would suggest that the conditions that allow participants to explicitly maintain an associative link between the cue and the goal will be less disruptive than conditions in which this link is more difficult to maintain. The auditory-visible condition allows participants to explicitly maintain an associative link; thus, interruptions in this condition should be less disruptive (i.e., faster resumption or more accurate performance) than the auditory-blank and visual interruption conditions. Because the auditory-blank and visual interruption conditions do not allow for easy maintenance of an associative link, resumption times and accuracy should be equal. Interrupting task performance should be equal across conditions.

The memory-for-goals cue association mechanism allows for explicit eye movement predictions. Extending memory for goals to the level of eye movement processes, during the interruption, participants in all conditions should attempt to fixate on relevant environmental cues in an effort to maintain an associative link to the suspended goal. The auditory-visible condition affords the greatest opportunity to maintain an associative link; thus, participants in this condition should fixate on relevant environmental cues more frequently than in the other conditions. Being able to maintain an associative link during the interruption in the auditory-visible condition should boost activation of the primary task goal and should result in more rapid goal-directed behavior upon resumption, because this goal can be retrieved quicker. This boost in activation should manifest itself as fewer fixations during the resumption lag and more fixations that are directed to goal-relevant parts of the interface. Participants in the other conditions, however, will have to fixate on several different areas of the interface in an effort to determine where to resume, resulting in more fixations during resumption.

## METHOD

### Participants

Participants were 54 undergraduate students.

### Materials

The primary task was a complex production task based on Li, Blandford, Cairns, and Young (2008), called the sea vessel task (Figure 1). The goal of the task was to fill orders for Navy sea vessels. An order sheet for two types of vessels was presented in the center of the screen in the manifest. To fill the order, information from the manifest had to be specified in five different modules; the modules corresponded to the vessel name, material, paint scheme, weapons, and


*Figure 1.* Screenshot of the primary task.

location of delivery. Before entering details in each module, the participant had to activate the module by clicking the respective module button in the Selector box (lower right-hand corner of Figure 1). There was a specific correct procedure for filling each order. After participants completed the modules, the order was processed (participants clicked “Process”) and then completed (participants clicked “Complete Contract”). The appendix contains a detailed description of the task.

The interrupting task consisted of three addition problems. Each problem required the participant to take the sum of two randomly generated single-digit addends ranging from 1 to 9. The problems were presented serially, and participants were given 5 s to answer each problem (including presentation time). The total interruption duration was 15 s. The problems were either presented aurally or visually. The time required to present each problem was equal in all conditions to keep ancillary processing approximately the same across interruption modality.

## Design

Interruption modality was manipulated between participants. There were three interruption conditions: auditory interruption with a full view of the primary task (auditory-visible), auditory interruption with a blank screen completely occluding the primary task for the duration of the interruption (auditory-blank), and a visual interruption that completely occluded the primary task (visual). In the visual interruption condition, the addition problems were presented in the center of the screen in the area of the interface that coincided with the Navy Manifest box on the primary task. No actions could be performed on the primary task during the interruption in any of the conditions. We assigned 18 participants randomly to each condition.

Control and interruption trials were manipulated within participants. Completing one order on the primary task constituted a trial. Participants completed 12 trials: half were interruption trials with two interruptions, and half were control with no interruptions. There were six interruption points: after filling information in on one of the five modules (after clicking “OK”) or after clicking the Process button. The interruptions occurred equally among these six positions. By the end of the experiment, participants were interrupted twice at each interruption point. The assignment of interruption and control trials and the ordering of the specific interruption locations were randomized.

## Procedure

Participants were seated 47 cm from the monitor. Before beginning the experiment, participants performed two practice trials (one control, one interruption). Participants then had to perform two (randomly selected) consecutive error-free trials before being permitted to begin the actual experiment. All participants were comfortable with the tasks after training.

Each participant was instructed to work at his or her own pace. During the interrupting task, participants were instructed to answer the addition problems when the solution was known by using the keypad. After resumption of the primary task, there were no indicators of where to resume, which minimized global place keeping (Gray, 2004). Errors on the primary task were signified by an auditory beep, and the participant had to make a correct action to continue.

## Measures

The resumption lag was the time-based measure of the disruptiveness of the interruption (Altmann & Trafton, 2004). The resumption lag was the time from the onset of the primary task screen following the interruption until the first click on the primary task interface. In the visual and auditory-blank conditions, the end of the interruption was signified by the appearance of the primary task interface. In the auditory-visible condition, a 300-ms screen flash signified the end of the interruption because the primary task was always visible to the participant. The resumption lag was compared with a measure of baseline performance, the interaction interval. The interaction interval was calculated for control trials and was the average time between clicking the OK button after entering information in a module and clicking the next selector button and the average time between clicking the Process and Complete Contract buttons.

Primary task accuracy may also be influenced by the interruption and was calculated as the percentage of errors made during the task. Selecting the wrong module (e.g., vessel, material, paint scheme, weapons, or location) or incorrectly clicking the Process or Complete Contract buttons constituted an error. Interruption task accuracy was calculated as the percentage of correctly answered addition problems. Failing to respond to an addition problem was counted as an incorrect response.

Eye track data were collected with the use of a Tobii 1750 operating at 60 Hz. A fixation was defined as a minimum of five eye samples within 30 pixels (approximately 2° of visual angle) of each other, calculated in Euclidian distance. Several areas of interest were defined to analyze the eye track data. Each of the five modules and their associated selector buttons and the Process and Complete Contract buttons were each unique areas of interest. The visual interruption was not colocated with any of the areas of interest. Each area of interest was separated by at least 2.5° of visual angle. Each of the modules subtended an area greater than 3°, the Process and Complete Contract buttons subtended 2°, and the selector buttons each subtended .75°.

Fixations during the interruption were categorized as relevant or irrelevant environmental cue fixations. Relevant environmental cues were operationally defined as modules or buttons on the interface that corresponded to the goal that was just completed prior to the interruption or to the goal that is to be completed after the interruption (i.e., retrospective and prospective). Both retrospective and prospective actions have been shown to be components of task resumption (Trafton et al., 2003).

Irrelevant environmental cues were any interface modules or buttons other than the just-completed or to-be-completed goal modules. For example, if a participant was interrupted after the paint scheme module, a fixation on the paint scheme module or selector button (i.e., the just-completed goal) or the weapons module or selector button (i.e., the to-be-completed goal) during the interruption interval would be a relevant environmental cue fixation. A fixation on the vessel module, or any module or button other than the paint scheme or weapons module and selector buttons, would be an irrelevant cue fixation. The Navy Manifest area of the interface, although relevant, was not included in this analysis, because this area overlapped with the location of the addition problems in the visual condition.

## RESULTS AND DISCUSSION

### Resumption Lag and Accuracy Data

First, the resumption lag was compared with the interaction interval, regardless of condition, to determine whether the interruption was disruptive to primary task performance. The resumption lag ($M$ = 3.46 s) was significantly longer than the interaction interval ($M$ = 2.26 s), $F(1, 53) = 108.6$, $MSE = 357421.1$, $p < .001$, indicating that the interruption was disruptive.

The effect of interruption modality on primary task performance was examined by comparing the resumption lags and primary task accuracy between conditions. The omnibus ANOVA comparing resumption lags was significant, $F(2, 51) = 13.8$, $MSE = 744391.3$, $p < .001$. Tukey HSD post hoc comparisons revealed that the auditory-visible condition ($M$ = 2.61 s, $SE$ = .16) was significantly shorter than the auditory-blank ($M$ = 3.7, $SE$ = .19, $p < .01$) and visual ($M$ = 4.1, $SE$ = .25, $p < .001$) conditions. The resumption lags in the auditory-blank and the visual conditions were not significantly different from each other ($p$ = .4, power > .8). The interaction intervals were compared between conditions to ensure that participants in the auditory-visible condition were not generally faster at performing the primary task. There was no significant difference in interaction intervals between the conditions, $F$ (2,51) = 1.5, $MSE$ = 266568.8, $p > .1$.

There was no significant difference in error rates on the primary task in the visual ($M$ = 1.4%), auditory-blank ($M$ = 2.8), and auditory-visible ($M$ = 2.1) conditions, $F$(2, 51) = 1.8, $MSE$ = 4.9, $p$ = .2. Also, there was no significant difference in interruption task accuracy between the visual ($M$ = 89.8%), auditory-blank ($M$ = 88.1), and auditory-visible ($M$ = 91.5) conditions, $F$(2, 51) = .6, $MSE$ = 86, $p$ = .5. The power to detect an effect was greater than .8 for both statistical tests.

The effect of interruptions on primary task performance was manifested in the resumption lag time, not primary task accuracy. The resumption lag data are consistent with the memory-for-goals theory. The interruptions were less disruptive in the auditory-visible condition, which, according to memory for goals, would afford the greatest opportunity to maintain an associative link between environmental cues and the target goal.

One explanation for the resumption lag differences between conditions is that the interrupting arithmetic task presented in one modality may be more difficult than another (e.g., visual arithmetic interruptions may be more difficult than auditory), and this difference may influence resumption time. To address this issue, an independent experiment ($N$ = 14) was conducted. This experiment showed there was no difference in accuracy when addition problems were presented visually or aurally (visual = 96.4%, aural = 95.7%, $F$ = .2, power > .85). Furthermore, there was no difference in Likert-type scale ratings of difficulty (1 = *easy*, 7 = *hard*) given the two modalities (visual = 2.4, auditory = 2.3, $F$ = .03, power > .85).

## Eye Data

Although the resumption time differences provide preliminary support for the memory-for-goals theory, at the crux of this theory as it applies to interruption modality is the association between environmental cues and the suspended primary task goal. Being able to maintain this association during the interruption should boost activation of the primary task goal and allow for faster resumption of the primary task. Memory for goals suggests that the auditory-visible condition affords the greatest opportunity to maintain the cue association, accounting for the faster resumption time compared with the other conditions.

If the memory-for-goals account is accurate, the cue association mechanism should be evident at the eye movement level in two ways. First, during the interruption, participants in the auditory-visible condition should be actively fixating on relevant environmental cues to maintain the association to the suspended task goal more frequently than in the other conditions. Second, during resumption, because the suspended task goal should have higher activation in the auditory-visible condition, participants should more quickly fixate on the to-be-resumed goal and should resume with fewer fixations as compared with the other conditions.

*Interruption period.* The eye movement data during each interruption was analyzed by examining whether there was a fixation to a relevant and/or irrelevant cue; a fixation to a relevant cue suggests that participants were attempting to maintain an associative link between the cue and the suspended primary task goal. Previous research has shown that a single fixation to a cue is enough to encode the cue and establish an associative link (Andrews, Ratwani, & Trafton, 2009); thus, we focused on whether participants made a single fixation to a relevant cue. For each participant in each condition, the percentage of interruptions with a relevant and/or irrelevant fixation was calculated. For example, if a participant fixated on a relevant cue in 9 of the 12 interruptions and fixated on an irrelevant cue in 6 of the 12 interruptions, the percentage of instances would be 75 and 50, respectively. In the auditory-visible condition, participants could fixate directly on the cues. In the auditory-blank and visual conditions, participants could fixate on the general spatial locations of the relevant environmental cues. Maintaining spatial location has been shown to be an important component of task resumption (Ratwani & Trafton, 2008).

A mixed-design ANOVA revealed a main effect of relevant versus irrelevant cue fixation instances, $F$(1, 51) = 815.7, $MSE$ = 114.5,

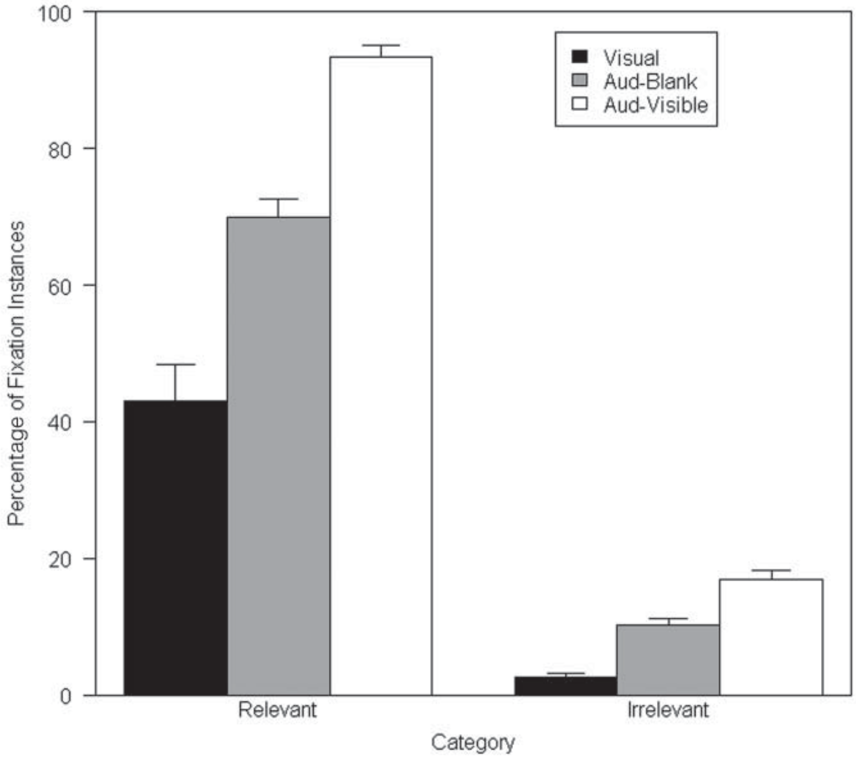


*Figure 2.* Instances of relevant and irrelevant cue fixation during the interruption interval by condition.

$p < .001$, and a main effect of condition, $F(2, 51) = 72.3$, $MSE = 131.1$, $p < .001$. The interaction between relevant and irrelevant fixation instances and condition was significant, $F(2, 51) = 25.4$, $MSE = 114.5$, $p < .001$, as shown in Figure 2. This interaction was attributable to an amplification of the interruption condition effect when the fixations were relevant. Tukey HSD post hoc comparisons were conducted to determine which conditions differed in the number of relevant fixation instances. Each condition was significantly different from one another (all *p*s < .001). The irrelevant fixation instances showed the same pattern of significant differences between conditions (all *p*s < .001).

The eye movement patterns during the interruption support the memory-for-goals theory. There were more instances of relevant cue fixations than irrelevant cue fixations in each of the conditions, which suggests that participants were attempting to maintain an associative link with the relevant environmental cue in each of the conditions. Participants in the auditory-visible condition, which resulted in the fastest resumption time, had more instances of relevant cue fixations than in the other conditions, which suggests that the greater opportunity for cue association during the interruption may be accounting for the faster resumption time. Participants in the auditory-visible condition also had more instances of irrelevant cue fixations than in the other conditions. However, compared with relevant cue fixations, the instances of irrelevant fixations were quite small (less than 20%).

Interestingly, participants in the auditory-blank condition had more instances of fixating on the spatial location of a relevant environmental cue than in the visual condition, yet this difference did not amount to resumption time differences between the two conditions. Thus, it appears that knowing the spatial location of the relevant cues may not be enough to boost activation of the suspended primary task goal. These data suggest that one must be able to directly see the cues to make the association between the suspended goal and the cues.

*Resumption lag.* Eye movements during the resumption lag (i.e., onset of the primary task to first action) were examined to determine whether the perceptual processes supported the memory-for-goals predictions. The greater number of relevant cue fixation instances during the interruptions in the auditory-visible condition should result in a high level of activation of the suspended primary task goal, resulting in the faster resumption times. At the eye movement level, participants in the auditory-visible condition should make fewer fixations during resumption, and these fixations should be immediately to the goal-relevant areas of the interface, reflecting the goal-directed behavior.

Participants in the other conditions, however, have to search memory and the interface for the next correct step, because these participants may not have benefited from as much cue association during the interruption. Thus, participants in the visual and auditory-blank conditions should make a greater number of fixations during resumption and may have to fixate on several different areas of the interface upon resumption to find the relevant environmental cues, which will then provide activation of the primary task goal.

There was a significant difference in the total number of fixations during the resumption lag between the visual ($M$ = 10.6), auditory-blank ($M$ = 9.5), and auditory-visible ($M$ = 7) conditions, $F(2, 51) = 7.2$, $MSE = 8.7$, $p < .05$. Tukey HSD post hoc comparisons demonstrate that the fewest fixations were made in the auditory-visible condition (all $p$s < .05), whereas there was no difference between the visual and auditory-blank conditions ($p = .5$).

To determine whether there were differences between the conditions in where participants looked during the resumption lag, the number of unique areas examined on the primary task interface was compared. A single fixation to an area constituted examining that area. For example, upon resumption, if a participant fixated on the vessel module and the weapons module (or associated selector), these would be two unique areas.

There was a significant difference in the number of unique areas examined between the conditions $F(2, 51) = 8.04$, $MSE = .81$, $p < .001$. Post hoc comparisons reveal that participants in the auditory-visible condition ($M$ = 3.4, $SE$ = .21) looked at fewer unique areas of the interface than in the visual ($M$ = 4.5, $SE$ = .24, $p$ < .01) and auditory-blank conditions ($M$ = 4.3, $SE$ = .17, $p$ < .01). There was no difference in the number of unique areas examined in the auditory-blank and visual condition ($p$ = .9). The greater number of unique areas examined in the auditory-blank condition and visual condition suggests that participants were searching for relevant task cues upon resumption in these conditions. Participants in the auditory-visible condition, however, did not have to examine as many cues to resume.

Given that there were overall resumption lag time differences between the three conditions (i.e., participants in the auditory-visible condition resumed more quickly), one might expect there to be fewer total fixations during the auditory-visible condition. However, the differences in the pattern of fixations, as evidenced by fewer fixations to different parts of the interface during the resumption lag, suggest that the faster resumption times during the auditory-visible condition were attributable to more goal-directed behavior during resumption.

## GENERAL DISCUSSION

The auditory-visible condition resulted in the fastest resumption times, whereas there were no differences between the auditory-blank and visual conditions. One explanation for the resumption lag differences between conditions is that participants in the auditory-visible condition were not performing the interrupting task, because the primary task interface was still available to them. Equal accuracy on the interrupting task rules out this explanation. Equal accuracy on the primary task rules out a speed-accuracy account of the resumption lag differences. The eye movement data during the interruption and resumption lag from each respective condition illustrated process differences that contributed to the resumption time differences. The reaction time and eye movement data support the memory-for-goals theory; interruption modality influences primary task resumption to the extent that the interruption allows for the maintenance of an association between environmental cues and the primary task goal.

In the auditory-visible condition, during the interruption, participants actively maintained an associative link between the suspended primary task goal and the relevant environmental cues more than 90% of the time. Maintaining the associative link boosted activation of the primary task goal and allowed for more goal-directed behavior upon resumption, accounting for the faster resumption times. Upon resumption, participants made fewer fixations overall and did not spend as much time fixating on multiple areas of the interface as in the other conditions. In the auditory-blank and visual conditions, participants did not maintain an association with environmental cues as often. Upon resumption, participants in the auditory-blank and visual conditions had a greater number of total fixations and fixated on several different areas of the interface as compared with the auditory-visible condition.

Given our focus on the resumption lag (Switch 2) and the fact that the experimental paradigm used here prohibited concurrent work on the primary task during the interruption, it is difficult to draw conclusions regarding the implications of preemption theory and multiple resource theory to interruption management. However, the results of this study illustrate the importance of having the ability to maintain an associative link between environmental cues and the suspended task goal. Interruption modality is important to the extent that it allows for the associative link to be maintained.

The importance of cue association during an interruption has several practical implications. When designing interruption management systems to reduce the time cost of interruptions, one should not assume that presenting an interruption in a modality different from the primary task will necessarily be beneficial. Rather, the focus should be on presenting an interruption in a modality that allows for the user to maintain an association between environmental cues on the primary task and the target goal. Furthermore, as evidenced by the data in this study, being able to directly fixate on the relevant environmental cue is important for cue association.

In computing environments, there are several ways of doing this. First, the interruption could be presented such that it does not completely occlude the primary task, allowing the user to fixate directly on cues in the primary task. Allowing explicit fixations to relevant cues or allowing users to have peripheral access to these cues may result in faster resumption times (Ratwani, Andrews, McCurry, Trafton, & Peterson, 2007). Second, increasing the monitor size may allow for access to cues on the primary task during an interruption. Researchers have shown that performance improves with increased display size (Tan, Gergle, Scupelli, & Pausch, 2006). Finally, one concern with having the primary task visible during an interruption is that the primary task may actually be distracting to performance on the interrupting task (although this was not the case in the experiment presented here). A possible solution is to design interfaces that allow for some detail of the primary task structure to be visible (e.g., spatial information plus "grayed-out" details of the primary task) during the interruption. This type of design may be beneficial because it allows the user to both concentrate on the interrupting task and maintain an association with the primary task goal.

## APPENDIX

### Procedure for Performing the Sea Vessel Production Task

- Begin the task by clicking the Next Order button. Orders for two different types of navy sea vessels will appear in the Navy Manifest window. The Navy Manifest provides specific information in regard to the Quantity, Vessel type, Material, Weapons, and Paint that should be included in each order.
- The first module to complete is the Vessel Module. Begin by clicking the Vessel Selector button from the Selector window. A message reading "Vessel Activated" will briefly appear indicating that you have activated the Vessel module. In the Vessel module, click the appropriate vessel types based on the Navy Manifest and enter in the specific quantities as indicated in the Navy Manifest. Click the Total button, calculate the sum of the two vessel types and enter the sum in the Total field. To complete the module click Ok.

*(continued)*

## APPENDIX (continued)

- The second module to complete is the Material Module. Begin by clicking the appropriate Selector button from the Selector window and enter in the details in the Material module based on the information provided in the Navy Manifest. Click Ok to complete the module.
- The third module to complete is the Paint Scheme Module. Begin by clicking the appropriate Selector button and enter in the details in the Paint Scheme module based on the information provided in the Navy Manifest. Click Ok to complete the module.
- The fourth module to complete is the Weapons Module. Begin by clicking the appropriate Selector button and enter in the details in the Weapons module based on the information provided in the Navy Manifest. Click Ok to complete the module.
- The fifth module to complete is the Location Module. Begin by clicking the appropriate Selector button and enter in the details in the Location module based on the information provided in the Navy Manifest. Click Ok to complete the module.
- Click the Process button to process the order. Upon clicking the Process button a pop-window will appear indicating the number of sea vessels you have ordered. Click the Ok button to acknowledge the message.
- Click the Complete Contract button to finish the order.

## ACKNOWLEDGMENTS

This work was supported by a grant from the Office of Naval Research to Greg Trafton and by a fellowship from the National Research Council to Raj Ratwani. As a work fully funded by the U.S. federal government, the content of the article is in the public domain.

## KEY POINTS

- Given a visual primary task, an auditory interruption that allows for visual access to the primary task results in a faster resumption time as compared with a visual interruption or an auditory interruption that occludes the primary task.
- Eye movement data suggest that participants in the auditory interruption condition with the primary task visible fixated on cues associated with the suspended primary task goal more frequently compared with the other conditions, and these participants fixated on the to-be-resumed goal more immediately upon resumption.
- Having the ability to actively associate visual cues with the suspended primary task goal accounts for the faster resumption time and supports predictions from the memory-for-goals model; interruption modality matters to the extent that it allows for cue association.
- These results suggest that in interruption-prone environments, computer systems should be designed to allow for visual access to the primary task when interruptions occur.

## REFERENCES

Altmann, E. M., & Trafton, J. G. (2002). Memory for goals: An activation-based model. *Cognitive Science*, *26*, 39–83.

Altmann, E. M., & Trafton, J. G. (2004). Task interruption: Resumption lag and the role of cues. In K. Forbus, D. Gentner, & T. Regier (Eds.) *In Proceedings of the 26th Annual Conference of the Cognitive Science Society* (pp. 43-48). Mahwah, NJ: Lawrence Erlbaum.

Altmann, E. M., & Trafton, J. G. (2007). Timecourse of recovery from task interruption: Data and a model. *Psychonomics Bulletin and Review*, *14*(6), 1079–1084.

Andrews, A. E., Ratwani, R. M., & Trafton, J. G. (2009). Recovering from interruptions: Does alert type matter? In *Proceedings of the 53rd Annual Meeting of the Human Factors and Ergonomics Society* (pp. 409–413). Santa Monica, CA: Human Factors and Ergonomics Society.

Bailey, B. P., & Iqbal, S. T. (2008). Understanding changes in mental workload during execution of goal-directed tasks and its application for interruption management. *ACM Transactions on Computer-Human Interaction*, *14*(4), 1-28.

Gonzalez, V., & Mark, G. (2004). Constant, constant, multi-tasking craziness: Managing multiple working spheres. In *Proceedings of the ACM CHI'04* (pp. 113–120). New York: Association for Computing Machinery.

Gray, W. D. (2004). Errors in interactive behavior. In W. S. Bainbridge (Ed.), *Berkshire encyclopedia of human-computer interaction: When science fiction becomes science fact* (pp. 230–235). Great Barrington, MA: Berkshire.

Hazeltine, E., & Ruthruff, E. (2006). Modality pairing effects and the response selection bottleneck. *Psychological Research*, *70*(6), 504–513.

Helleberg, J., & Wickens, C. D. (2002). Effects of data link modality and display redundancy on pilot performance: An attentional perspective. *International Journal of Aviation Psychology*, *13*(3), 189–210.

Helleberg, J., Wickens, C. D., & Goh, J. (2003). Traffic and data link displays: Auditory? Visual? Or redundant? A visual scanning analysis. In *Proceedings of the 12th International Symposium on Aviation Psychology*. Dayton, OH: Wright State University Press. Retrieved from http://www.humanfactors.uiuc.edu/Reports&PapersPDFs/isap03/helwicgoh.pdf

Ho, C.-Y., Nikolic, M. I., & Sarter, N. B. (2001). Multimodal information presentation in support of timesharing and effective interruption management. In *Proceedings of the 20th Digital Avionics Systems Conference* (pp. 5D2/1–5D2/8). Los Alamitos, CA: Institute of Electrical and Electronics Engineers.

Ho, C.-Y., Nikolic, M. I., Waters, M. J., & Sarter, N. B. (2004). Not now! Supporting interruption management by indicating the modality and urgency of pending tasks, *Human Factors*, *46*, 399–409.

Hodgetts, H. M., & Jones, D. M. (2006a). Contextual cues aid recovery from interruption: The role of associative activation. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *32*, 1120–1132.

Hodgetts, H. M., & Jones, D. M. (2006b). Interruption of the Tower of London task: Support for a goal activation approach. *Journal of Experimental Psychology: General*, *135*, 103–115.

Horrey, W. J., & Wickens, C. D. (2004). Driving and side task performance: The effects of display clutter, separation, and modality. *Human Factors*, *46*, 611–624.

Iani, C., & Wickens, C. D. (2007). Factors affecting task management in aviation. *Human Factors*, *49*, 16–24.

Latorella, K. A. (1998). Effects of modality on interrupted flight deck performance: Implications for data link. In *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (pp. 87–91). Santa Monica, CA: Human Factors and Ergonomics Society.

Li, S. Y. W., Blandford, A., Cairns, P., & Young, R. (2008). The effect of interruptions on postcompletion and other procedural errors: An account based on the activation-based goal memory model. *Journal of Experimental Psychology: Applied*, *14*(4), 314–328.

Liu, Y., & Wickens, C. D. (1992). Visual scanning with or without spatial uncertainty and divided and selective attention. *Acta Psychologica*, *79*, 131–153.

McFarlane, D. (2002). Comparison of four primary methods for coordinating the interruption of people in human-computer interaction. *Human-Computer Interaction*, *17*(1), 63–139.

Monk, C. A., Boehm-Davis, D. A., & Trafton, J. G. (2004). Recovering from interruptions: Implications for driver distraction research. *Human Factors*, *46*, 650–663.

Monk, C. A., Trafton, J. G., & Boehm-Davis, D. A. (2008). The effect of interruption duration and demand on resuming suspended goals. *Journal of Experimental Psychology: Applied*, *14*, 299–313.

Ratwani, R. M., Andrews, A. E., McCurry, M., Trafton, J. G., & Peterson, M. S. (2007). Using peripheral processing and spatial memory to facilitate task resumption. In *Proceedings of the 51st Annual Meeting of the Human Factors and Ergonomics Society* (pp. 224–248). Santa Monica, CA: Human Factors and Ergonomics Society.

Ratwani, R. M., & Trafton, J. G. (2008). Spatial memory guides task resumption. *Visual Cognition*, *16*(8), 1001–1010.

Sarno, K. J., & Wickens, C. D. (1995). The role of multiple resources in predicting time-sharing efficiency: An evaluation of three workload models in a multiple task setting. *International Journal of Aviation Psychology*, *5*(1), 107–130.

Spence, C. (2001). Crossmodal attentional capture: A controversy resolved? *Advances in Psychology*, *133*, 231–262.

Tan, D. S., Gergle, D., Scupelli, P., & Pausch, R. (2006). Physically large displays improve performance on spatial tasks. *ACM Transactions on Computer-Human Interaction*, *13*(1), 71–99.

Trafton, J. G., Altmann, E., & Brock, D. (2005). Huh, what was I doing? How people use environmental cues after an interruption. In *Proceedings of the 49th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 468–472). Santa Monica, CA: Human Factors and Ergonomics Society.

Trafton, J. G., Altmann, E. M., Brock, D. P., & Mintz, F. E. (2003). Preparing to resume an interrupted task: Effects of prospective goal encoding and retrospective rehearsal. *International Journal of Human-Computer Studies*, *58*, 583–603.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63–101). Orlando, FL: Academic Press.

Wickens, C. D. (2002). Multiple resources and performance predictions. *Theoretical Issues in Ergonomics Science*, *3*(2), 159–177.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*, 449–455.

Wickens, C. D., & Colcombe, A. (2007). Dual-task performance consequences of imperfect alerting associated with a cockpit display of traffic information. *Human Factors*, *49*, 839–850.

Wickens, C. D., Dixon, S., & Seppelt, B. (2005). Auditory preemption versus multiple resources: Who wins in interruption management? In *Proceedings of the 49th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 463–467). Santa Monica, CA: Human Factors and Ergonomics Society.

Wickens, C. D., & Liu, Y. (1988). Codes and modalities in multiple resources: A success and a qualification. *Human Factors*, *30*, 599–616.

Wickens, C. D., & McCarley, J. S. (2008) *Applied attention theory*. Boca Raton, FL: CRC Press.

Raj Ratwani is a senior research scientist at Perceptronics Solutions, Inc., in Arlington, Virginia. He received his PhD in psychology in 2008 from George Mason University in Fairfax, Virginia, where he is currently an affiliate.

J. Gregory Trafton is an engineering psychologist at the Naval Research Laboratory in Washington, D.C. He received his PhD in psychology from Princeton University in Princeton, New Jersey, in 1994.

*Date received: March 30, 2009*
*Date accepted: April 13, 2010*