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ORIGINAL ARTICLE

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# Tactile interruption management: tactile cues as task-switching reminders

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**Abstract** Tactile cuing has been suggested as a method of interruption management for busy visual environments. This study examined the effectiveness of tactile cues as an interruption management strategy in a multi-tasking environment. Sixty-four participants completed a continuous aircraft monitoring task with periodic interruptions of a discrete gauge memory task. Participants were randomly assigned to two groups; one group had to remember to monitor for interruptions while the other group received tactile cues indicating an interruption's arrival and location. As expected, the cued participants evidenced superior performance on both tasks. The results are consistent with the notion that tactile cues transform the resource-intensive, time-based task of remembering to check for interruptions into a simpler, event-based task, where cues assume a portion of the workload, permitting the application of valuable resources to other task demands. This study is discussed in the context of multiple resource theory and has practical implications for systems design in environments consisting of multiple, visual tasks and time-sensitive information.

**Keywords** Interruption management · Tactile cues · Task-switching · Prospective memory

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## 1 Introduction

Advances in technology and telecommunications continue to increase the number of concurrent demands and potential for interruptions in many work settings. The successful management of interruptions is becoming an increasingly important aspect of effective performance in many jobs. Research in fields such as software engineering (e.g., Perlow 1999), aviation (e.g., Sarter 2001), medicine (e.g., Coiera et al. 2002), and organizational management (e.g., Mintzberg 1973) have shown how multiple demands on attention can create performance problems.

Interruption management has been defined by Latorella (1996) as the detection, interpretation, and integration of interruptions within ongoing task performance. Experimental research on task-switching (e.g., Cellier and Eyrolle 1992; Jersild 1927; Rogers and Monsell 1995; Spector and Biederman 1976) has demonstrated that people struggle with transitions from one task to another, resulting in slower performance and increased errors. Task-switching research (e.g., Spector and Biederman 1976) has indicated that it can be difficult for people to remember to switch from one mental process to another while engaged in current activity. One method that can be used to enhance task-switching is the utilization of cues to inform people of new events that arise amid ongoing performance (e.g., Cellier and Eyrolle 1992). In other words, cues can be used to inform users of an impending task, and facilitate management of an interruption. In this paper we investigate the effectiveness of cues as an interruption management strategy in a multiple-task environment.

While cues can offer a ready method to enhance task-switching, the use of visual and auditory cues has been found to be problematic in certain situations (see Sarter 2000 for a review of cuing in aviation). For instance, in noisy or busy visual environments, auditory and visual cues can go unnoticed (e.g., Akamatsu et al. 1995; Edworthy et al. 1995; Sarter 2001). Alternatively, when cues have been designed to be more distinct from background stimuli, disruption of ongoing task performance can occur (e.g., Sarter 2000). Sarter (2000) suggested that, under some circumstances such as when the auditory or visual channel is heavily taxed, the tactile modality may be more effective for cue delivery. Consistent with this notion, a recent study by Hopp et al. (2005) found that spatially informative tactile cues to the left or right shoulders of individuals enabled them to attend to more peripheral interruptions and to respond faster to those interruptions than when no cues were presented. Importantly, tactile cues did not significantly disrupt primary task performance. Despite these promising findings for the effectiveness of tactile cues to signal the arrival of an interrupting task, Hopp et al. did not examine the cognitive mechanisms associated with tactile cuing benefits.

One explanation for the effectiveness of tactile cues is that the cues may serve to reduce the cognitive load of individuals who struggle to spread their attention and other cognitive resources (e.g., memory) across multiple sources of input. For instance, individuals without a method of interruption management, while engaged in a continuous primary task, have to remember to disengage from the primary task and engage in a scan of the environment for incoming stimuli. Therefore, tactile cues might aid performance by removing a memory component of task-switching, thus reducing the cognitive workload. The purpose of this study was to determine if tactile cues reduced the load on prospective memory in multi-tasking environments.

## 2 Tactile cuing as a method of interruption management

Previous theory and research (for reviews see Moray 1981, 1986) have often framed task-switching as an issue of optimal sampling from a variety of channels of information. Therefore, cuing can aid operators in busy environments by more efficiently directing attention to where it is most critically needed at a particular time. Specifically, Cellier and Eyrolle (1992) suggested that a cue signaling when a secondary task requires attention may assist in the inhibition of cognitive resources being used on a primary task and the activation of different cognitive resources needed for the secondary task. Thus, it appears that cuing has potential as a method of interruption management through its capability to direct attention and to facilitate cognitive processing.

Cues, in addition to signaling the arrival of a new task, can also be used to communicate supplemental information about the task in order to further enhance efficiency. For instance, Ho et al. (2003) implemented cues that conveyed information about the nature and urgency of a pending task during performance of an air traffic control task. Likewise, Hopp et al. (2005) employed cues that indicated the arrival and spatial location (i.e., left or right) of an interrupting task in a spatially complex task environment. However, although potentially beneficial, such additional information could also overload an operator and interfere with ongoing task performance. As such, the sensory modality through which the cues are delivered is a critical consideration with respect to the operator's workload.

It has been suggested (Gilliland and Schlegel 1994; Sarter 2000; Sklar and Sarter 1999) that the provision of cues through the tactile modality can hold advantages over the presentation of these cues through other modalities. Multiple resource theory (Wickens 1984) implies that the cognitive resources used to process information from one modality (e.g., tactile) do not compete with the resources used to process input from another modality (e.g., visual). Given that many tasks require the processing of visual and auditory information, concurrently presenting cues in these modalities may not be effective. For example, cues may become lost (or alternatively, too distracting) in busy visual and auditory environments. In contrast to the very commonplace visual and auditory nature of tasks, comparatively few tasks are highly reliant on information obtained through the tactile modality. Therefore, the addition of cues that are tactile in nature may be more easily detected and less intrusive in the context of an ongoing visual or auditory task performance.

The use of tactile communication has been explored to some extent within the aviation domain (e.g., Gilliland and Schlegel 1994; Sklar and Sarter 1999; Zlotnik 1988) where pilots and air traffic controllers are faced with overburdened visual and auditory channels. Generally, tactile communication has been found to be detectable, yet there have been conflicting results about the possibility of interference with ongoing performance. Still, researchers have been optimistic about the potential of tactile communication to convey different types of information. As many jobs in aviation are characterized by multiple demands requiring rapid switching between sources of information (Sarter 1996; Sarter and Woods 1992, 1995, 1997; Wickens 2002), it may be particularly beneficial to explore the use of tactile cues in the aviation domain.

A recent study by Hopp et al. (2005) demonstrated the potential effectiveness of tactile cuing as a method of interruption management. While performing a primary visual aircraft monitoring task, tactile cues in the form of short vibrations to the shoulders of individuals indicated the arrival and spatial location of a discrete secondary task. The vibrations were presented on the ipsilateral shoulder to the computer screen on which the interrupting task appeared, thus creating a method of spatially informative cuing. Hopp et al. found that individuals receiving tactile cues attended to more interruptive tasks and responded faster than the participants without cues. Importantly, the addition of the tactile cues did not disrupt primary task performance. These findings are congruent with the notion that tactile cues offer a promising method for directing attention to interrupting tasks without interfering with concurrent cognitive processing.

### 2.1 Tactile cues as task-switching reminders

The Hopp et al. (2005) study demonstrated that the provision of spatially informative tactile cues enabled participants to attend to interruptive tasks which appeared outside of their visual foci. One way of thinking about this performance benefit is to consider the workload of the two groups. Individuals without cues need to hold in memory the intention to check the environment for interruptive tasks, while cued individuals can rely on the cue rather than their memory. Hence, a performance advantage for tactile cueing may result from the reduced memory load in the cued participants. The purpose of this study was to examine whether tactile cuing can render benefits in terms of memory function. To test this notion, a paradigm similar to that in Hopp et al. was used, but the interruptive task was modified so as to include a memory component. If tactile cuing indeed reduces memory workload, cued participants should experience less demand compared to uncued participants. Hence, to the extent that memory resources are freed up by the presence of tactile cues, cued participants would then outperform uncued participants on other memory-related task components. Conversely, if the primary benefit of the cue is related only to attention management, then the additional memory component of the secondary task should not cause a reduction in secondary task performance.

### 2.2 Prospective memory

In busy environments, one of the reasons operators may fail to attend to interruptions is because they become absorbed in the primary task and forget to take necessary actions (Einstein and McDaniel 1996). For instance, research in the aviation domain (Sarter et al. 1997) indicates that operators often make errors of omission when they fail to take necessary action in the context of other demands. Such challenges can be considered an issue of prospective memory (Baddeley and Wilkins 1984). Prospective memory is defined as memory to perform an intended action in the future.

Traditional studies of task-switching (e.g., Koch 2003; Spector and Biederman 1976) have found that external cues act as reminders when switching between two tasks. Cues can be used to support the performance of prospective actions by triggering the action, the content of the action, or both (Vortac et al. 1995). Therefore, in the context of tactile cuing as interruption management, a directional tactile cue might be a particularly effective trigger for both the action and the content, in that it reminds participants that they need to do something in the midst of primary task performance and it indicates what needs to be done by directing attention to the appropriate monitor. Hence, tactile cues may serve as effective reminders that directly guide individuals to achieve their intended actions.

### 2.3 Event-based versus time-based prospective memory tasks

Theoretical accounts of prospective memory tasks suggest a distinction between event-based tasks (i.e., the need to perform an action when an external event occurs) and time-based tasks (i.e., the need to perform an action at a certain time or after a certain amount of time has elapsed) (Einstein and McDaniel 1990). As examples, consider the following everyday scenarios in which cues are used to support prospective memory. In order to remember to do something, such as relay a message upon seeing a particular colleague, one might write a note reminding oneself. This need to pass on a message to a colleague when they enter one's office is an event-based task (i.e., the action is triggered by the colleague entering the office). Another example of prospective memory cuing occurs when an individual uses a computer alarm to signal the need to attend an important meeting at a particular time. The need to attend a meeting is a time-based task (i.e., the action is triggered by the passage of time). However, setting a computer alarm for the meeting transforms the time-based task into an event-based task. In other words, rather than remembering to keep track of the time, the alarm acts as an external event to signal the action, making it an event-based task. In the context of our study, tactile cues may similarly serve to transform the time-based task of remembering to periodically check the peripheral monitors into an event-based task of simply responding to the cues.

The use of external events to signal performance of a prospective action provides environmental support for that action (Einstein and McDaniel 1996). Event-based tasks can be accomplished without creating much demand on one's cognitive resources (McDaniel and Einstein 2000). In this way, the external event, or cue, assumes a portion of the cognitive workload. The notion of multiple resources suggests that cognitive resources can be divided and allocated to handle concurrent demands; if the demand is not maximized, there exists spare capacity, or residual resources, which can be applied to other task components (Wickens 2002). As such, individuals relying on cues may be able to use fewer cognitive resources than individuals without cues and, therefore, should have spare capacity to apply elsewhere. Based on this reasoning, cued participants within the paradigm should have more memory resources available to handle other memory-related task components, compared to the uncued participants who need to employ additional resources to remember to periodically switch between the tasks.

In order to test this notion, a memory component was added to the interruptive task used in Hopp et al. (2005). The modified interruptive task asked participants to compare a current gauge reading with the previous gauge reading. Therefore, participants had to remember the most recent gauge reading while performing the primary task in order to recall that information for the next interruptive task. Because the modified task paradigm requires memory resources to maintain the most recent gauge reading in memory, if the cued participants have greater spare capacity of memory resources, then they can be predicted to outperform uncued participants in terms of accuracy on the interruptive memory task (i.e., have fewer errors). In other words, because a portion of the memory resources needed for task-switching are spared by the use of tactile cues, the cued participants should be able to allocate those memory resources to the maintenance and recall of the prior gauge reading. Conversely, if memory in the uncued group is taxed by the need to initiate task-switching, then fewer memory resources will be available to recall the most recent gauge reading. Based on findings in Hopp et al. (2005), we also expected the cued participants to attend to more interruptive tasks and to respond faster to the interruptive tasks compared to the uncued participants.

H1: Cued participants will make fewer errors on the interruptive task than uncued participants.
H2: Cued participants will complete a higher percentage of the interruptive tasks than uncued participants.
H3: Cued participants will respond faster to interruptions than uncued participants.

Moreover, the cognitive resource advantage for the cued participants should also lead to differential primary task performance. The primary aircraft task requires memory for the action rules which dictate when and where different aircraft can be acted upon. Analysis of this task indicated that participants often reported mentally restating the rules of the task upon returning to it following an interruption. Support for such a notion can be found in a study by Cutrell et al. (2001) which suggested that participants frequently requested reminders of their goals on a primary task after having been interrupted. Additionally, prior to disengaging from one task, participants may also prepare for interruptions by creating prospective memories for actions to complete upon returning to the primary task. Therefore, if the cued participants have comparatively more available memory resources, they should be able to resume primary task performance with greater ease and efficiency. Hence, cued participants were expected to perform better than uncued participants on the primary aircraft task.

H4: Cued participants will make fewer errors on the primary task than uncued participants.

## 3 Method

### 3.1 Participants

Participants, who received credit toward a course requirement, were 64 undergraduates (30 males) enrolled in an introductory psychology course at a large, public university. Participants were randomly assigned to be in the treatment group ($n = 32$; 56% male) or the control group ($n = 32$; 38% male).

### 3.2 Equipment

The experiment was conducted on a computer system having three monitors, with the primary task presented on the center screen. The two additional monitors that presented the interruptive task were positioned laterally, one on each side of the participant, at 90° angles from the center screen. The side screens were placed outside of the participant's peripheral vision, thus requiring a turn of the head for the screen to be scanned.

Participants in the treatment groups donned a vest through which the tactile cues were delivered. More specifically, the lightweight, nylon vest had two vibrators sewn into the back at the shoulder blade areas. The vibrators, each weighing approximately one ounce, were eccentric motors of the type commonly used in cell phones and pagers. Vibrators were powered by a 1.5 V D-Cell battery and the characteristic frequency of vibration was approximately 30 cycles per second. The battery and associated switching hardware were located in a box that was connected to the vest by detachable cables. A Visual BASIC program activated the vibrator at the appearance of the interrupting task. The vibrator was activated for approximately 1 s on the side nearest to which the task appeared.

### 3.3 Task paradigm

The tasks were based on those employed by Hopp et al. (2005). The primary task required participants to engage in a continuous, visual task modeled after an aircraft monitoring scenario. The interruptive task, consisting of a discrete, visual gauge reading task, appeared periodically throughout the scenario, interchanging pseudorandomly between left and right peripheral screens.

### 3.4 Primary aircraft task

Three scenarios were designed to be of equal difficulty. Each scenario was 10 min in length and presented a total of 190 aircraft. Aircraft appeared on the screen and needed to be classified as hostile, perceived hostile, friendly, or perceived friendly based on their outer shape (e.g., circles, squares, diamonds), inner shape (e.g., crosses, dots), and color. Once classified, participants could either warn or fire upon certain objects, following the rules of engagement. For example, a symbol with a cross inside was classified as Perceived Hostile and needed to be warned if it entered the warning zone. Once warned, if that aircraft continued to enter the firing zone it should be fired upon. Participants used the mouse to select, warn, and fire upon enemy objects. The primary task screen consisted of a map with a yellow warning zone and a red firing zone. A graphic representation of the task is provided as Fig. 1.

Within each 60-s time period, the number of planes that entered view ranged from 10 to 30, with the number of those being hostile or potentially hostile ranging from 7 to 17. On average, two-thirds of the planes that crossed the screen required action from the participant. A random sample of seven scenarios was selected to provide an estimate of actions performed. Within this sample of scenarios, participants ranged from 18 to 44 mouse clicks per minute, with an average of 30 mouse clicks per minute.

A summarized count of correct decisions and errors was displayed to the participant at the end of each scenario. The dependent variables for this task were the number of hits, misses, false alarms, and correct rejections for each scenario. Hits occurred when participants correctly took action (warned or fired upon enemy objects). Misses occurred when participants failed to take action. False alarms occurred when participants erroneously took action against a non-hostile object. Correct rejections occurred when participants did not act when action was not required.

### 3.5 Interruptive gauge memory task

A depiction of the gauge task is shown in Fig. 2. The gauge task consisted of two gauges side by side and a question written beneath the gauges. The participant did not know when to anticipate a gauge question, to what side to expect its appearance, or for how long the question would remain visible. The time between questions ranged from 20 to 70 s and was varied to appear unpredictable. Additionally, the duration of presentation for each question varied from 10 to 20 s. Scenarios were counterbalanced so that all permutations of question types and locations (left or right screen) were presented equally within each scenario.

Questions alternated between two types. The first question presented was a “More or Less” question, which was one of six variations querying whether the gauges were more or less than 5, 10, or 15 units apart. The second type of question presented was a “Comparison” question, which varied between two forms regarding whether the current gauge readings were farther apart or closer together than the previous gauge readings. In order to consistently provide a correct answer for the “Comparison” questions, participants would need to retain in memory the gauge distance from the most recent question. For instance, the first display for the “More or Less” question may have shown two gauge readings that were 7 units apart. Participants needed to remember that number in order to determine whether or not the next two gauge readings were farther apart or closer together than 7 units. Participants responded to both question types by pressing ‘y’ or ‘n’ on the keyboard for ‘yes’ or ‘no’ answers. Each 10-min scenario presented a total of 15 gauge task interruptions, alternating between eight “More or Less” and seven “Comparison” questions.

The number of questions answered correctly was displayed to the participant at the end of each scenario. The dependent variables used for this task were the proportion of questions attempted, the proportion of questions answered incorrectly, and the average response time for correct responses.

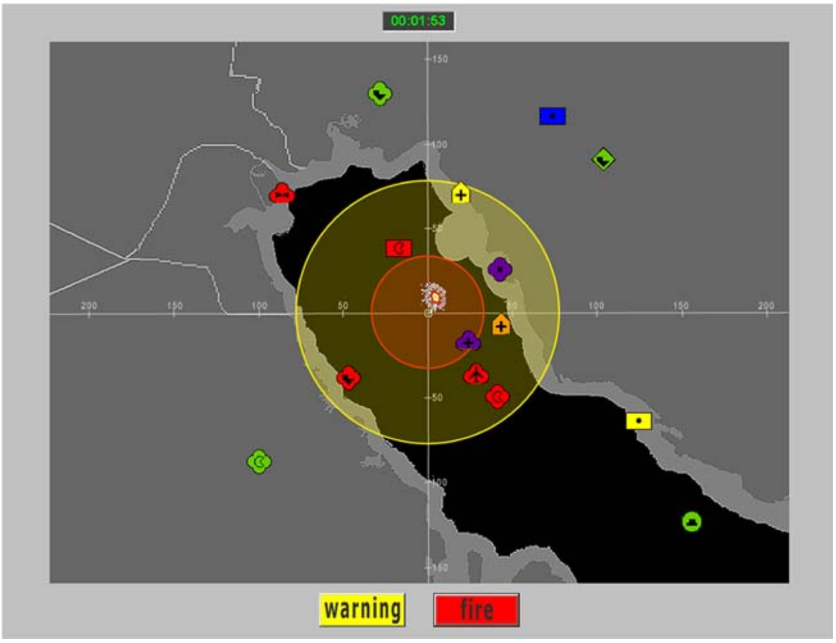
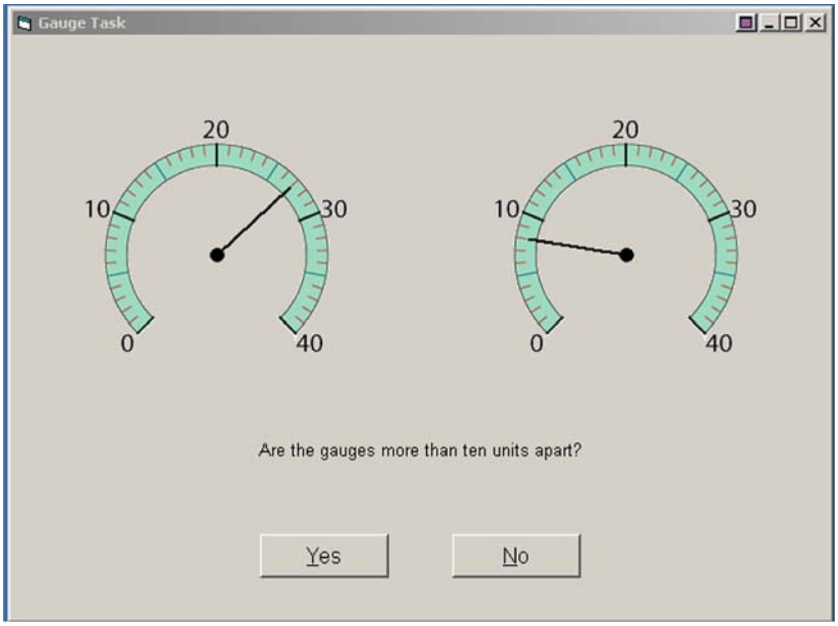


**Fig. 1** Example display from the primary task: aircraft monitoring



Are the gauges more than ten units apart?

**Fig. 2** Example display from the interruptive task: gauge reading

### 3.6 Experimental conditions

The control group consisted of 32 participants that were instructed to perform the aircraft monitoring task while remembering to periodically check the side screens for the appearance of the gauge task. The treatment group consisted of 32 participants that performed the same tasks but with the aid of tactile cues.

### 3.7 Subjective workload measures

Participants in the control group responded to eight questions regarding the difficulty of both tasks separately and in combination, time pressure, subjective performance, mental effort, frustration/stress, and physical discomfort. Ratings of each item were made using a 10-point Likert-type response scale (1 = low to 10 = high). Participants in the treatment group responded to the same eight questions and an additional three questions. The additional questions asked participants to rate the helpfulness of the cues, the annoyance of the cues, and whether they immediately switched their attention upon sensing the cue versus waiting for an opportune time to switch.

### 3.8 Procedure

All participants completed the experimental procedure on an individual basis. Upon arrival, participants filled out consent forms and were seated at the computer, in a non-swiveling chair. Participants completed 2-min training sessions for both tasks in order to familiarize themselves with the nature of each task in isolation. After the experimenter ensured understanding of each separate task, participants began the actual scenarios presenting both tasks. Participants completed three 10-min scenarios with 1-min rest breaks between scenarios. Upon completion of the third scenario, participants filled out the post-session questionnaire.

## 4 Results

### 4.1 Interruptive memory task performance

The first question examined was whether the treatment group would be more attentive to the interruptive task, indicated by more efficient attention-switching. *T*-tests compared the proportion of interruptions attempted in the treatment group to that in the control group, as well as the average time taken to correctly answer the interruptions. Analyses indicated that the treatment group attempted a significantly greater proportion of interruptive questions (mean proportion = 0.95 and 0.79 for the treatment and control groups, respectively, $t(36) = -5.08$, $p < 0.01$, $d = 1.69$) and responded significantly faster when producing a correct answer (mean = 6.36 s and 7.16 s for the treatment and control groups, respectively, $t(53) = 2.32$, $p < 0.01$, $d = 0.64$) compared to the control group. Thus H2 and H3 were supported.

The next question was whether the treatment group would perform more accurately on the interruptive memory task compared to the control group. A *t*-test compared the error rates of the two groups, revealing that while the treatment group's error rate was lower compared to the control group (0.21 vs. 0.25, respectively), this difference was not statistically significant ($t(62) = 1.69$, *ns*). That is, for those secondary questions attempted, the error rates were not significantly different

Table 1 Aircraft monitoring task performance

| Dependent variable | Treatment group ($n = 32$) | Control group ($n = 32$) |
|---|---|---|
| Hits | 10,923 (90.5%) | 9,866 (87.0%) |
| Misses | 1,145 (9.5%) | 1,466 (13.0%) |
| False alarms | 552 (7.2%) | 1,196 (14.0%) |
| Correct rejections | 7,103 (92.8%) | 7,080 (86.0%) |

*Note*: Corresponding action rates provided in parentheses

between groups. Thus H1 was not supported directly. However, since the cued participants responded to significantly more questions, their total number of correct responses was larger than the uncued participants. In practical terms, cuing was associated with a greater number of correct answers.

## 4.2 Primary aircraft task performance

In taking action against the hostile and perceived hostile objects, participants' actions were classified as hits, misses, false alarms, or correct rejections. Table 1 shows the number of occurrences of each of the four types of responses across the three conditions. A chi-square test examined whether the total number of hits, misses, false alarms, and correct rejections in the tactile and control groups differed from the expected values. The results ($\chi^2(3) = 330.17$, $p < 0.05$) showed that there was, in fact, a significant difference in aircraft task performance across the two groups. Cramer's phi was found to be 0.09, which is interpreted to reflect that 9% of aircraft task performance can be attributed to the presence of the tactile cues. Thus H4 was supported.

Signal detection theory was used to further examine the differences in performance between the two groups. Signal detection theory provides a method of assessing the decision-making process when evaluating different classes of items. This method provides a measure of the participants' sensitivity, or their ability to detect a signal; as well as a measure of criterion, or bias in favoring a particular type of response in ambiguous situations. The sensitivity statistic represents the standardized difference between the means of the signal present and signal absent distributions. Thus, larger values indicate greater sensitivity in detecting a difference between distributions. The treatment group had greater sensitivity ($d' = 2.77$) than the control group ($d' = 2.21$), which means that the treatment group had a lower probability of errors. The control group's criterion was lower ($\beta = 1.08$) compared to the treatment group's criterion ($\beta = 1.46$), which means that the control group was more likely to fire in ambiguous situations. Thus, the control group demonstrated a preference for false alarms. However, the control group also had a higher miss rate compared to the treatment group, which indicates that control participants were not only more liberal in their actions, but were less able to discriminate as well.

Overall, these analyses suggest that the treatment group performed with greater accuracy on the aircraft monitoring task compared to the control group. In this primary task, participants in the control group not only had a greater tendency to miss enemy targets, but were more prone to haphazardly firing at friendly targets. In military applications, a bias towards miss errors is often preferable considering the base-rate incidence of hostile and friendly aircraft in busy airspace (Smith et al. 2004). A bias towards false alarms and a high miss rate obviously would have extremely negative consequences in a real world setting.

## 4.3 Subjective workload

Participant responses on the workload questionnaire (i.e., the eight questions in common across the two conditions) were summed to form a composite workload rating. No significant effect of group on subjective workload perceptions was observed (43.3 and 44.2 for the treatment and control groups, respectively, $t(62) = 0.35$, *ns*; $d = 0.089$). These data therefore offer no evidence that the groups differ greatly in their subjective perceptions of workload or task difficulty.

The responses to the three treatment group questions regarding the tactile cues were also examined. Responses suggested that the tactile cues were helpful (mean = 9.38 on 10 point scale, SD = 1.01) and of low annoyance ($M = 2.75$, SD = 2.30). The majority of participants (94%) indicated that most of the time they waited to switch their attention until a desired action was completed.

Overall, these findings demonstrated that tactile cues produce considerable performance advantages on both the interruptive and primary tasks when memory resources are required for task processing. It appears that the uncued participants struggled not only in their ability to handle the interruptions but in their ability to manage the primary task as well. Thus, it seems that the memory load placed a significant burden on participants that had to remember on their own to monitor the environment.

## 4.4 Comparison to Hopp et al. (2005)

It is informative to compare the results of this study with those found in a similar study (Hopp et al. 2005). The procedures and tasks were identical with the exception of the memory component of the interruptive task. That is, in Hopp et al., the secondary gauge task asked only questions about the current distance between the gauges, and never any questions that would require participants to recall the distance from the previous question. The addition of the memory component resulted in a considerably greater difference between the cued and uncued participants in terms of the proportion of interruptions attempted. Specifically, Cohen's *d* for the difference in proportion attempted in the current study was 1.69 (control = 0.79; treatment = 0.95) compared to 1.09 (control = 0.86; treatment = 0.94) in the Hopp et al. study. Uncued participants in the current study appeared to suffer more drastically in their ability to notice incoming tasks. This observation supports the idea that the memory requirements of the interruptive task did, in fact, pose challenges for task-switching in the uncued participants. As such, the management of memory resources may be an important consideration in contexts such as this, where one has prospective memory requirements amid ongoing performance.

Additionally, the error rates on the interruptive task were greater in the current study (control = 0.25; treatment = 0.21) compared to those found in Hopp et al. (2005) (control = 0.19; treatment = 0.17). This observation implies that performing the memory-intensive interruptive task was more difficult compared to the original gauge task for participants in both conditions. Further, the error rate differential between the two groups became greater in the current study (Cohen's $d = 0.43$ in current study compared to 0.21 in Hopp et al.), suggesting that the tactile cues provided an even greater benefit when a more resource-intensive task was involved.

Finally, in contrast to the current experiment, the Hopp et al. (2005) study did not reveal any primary task performance differences between the two groups. Hence, it appears that the increased memory load in the secondary task produced greater challenges for primary task performance in the uncued participants. Specifically, the uncued participants in the current study likely employed memory resources to guide task-switching as well as interruptive task processing, which may not have left enough capacity for optimal primary task performance. As mentioned previously, memory resources may be required to recall the action rules for the primary task as well as to plan performance of prospective actions upon primary task resumption. The cued participants in the current study appeared to possess superior management of the memory-related components in the primary task.

## 5 Discussion and conclusions

The use of tactile cues was shown to be effective in managing interruptions in multi-tasking environments. Cued participants responded to a greater proportion of interruptions, and responded faster than uncued participants. The cued participants performed better at the primary task as well. And although the error rates on the interruptive task were not different between groups, the cued participants produced a greater number of correct answers.

This research was framed as an investigation into the cognitive mechanisms by which cuing strategies assist task-switching. It has been shown that cuing is an effective attention-management strategy, but does it also reduce the load on memory resources? Overall, the results of this study support the notion that memory is an important consideration in interruption management. Generally, this research suggests that tenets of multiple resource theory should be considered when designing systems in multiple task situations. For instance, the tactile cues utilized a perceptual modality distinct from the visual modality used in task processing in order to minimize interference (Wickens 1984). Additionally, the results illustrated how tactile cuing can compensate for one's finite cognitive resources by assuming a portion of the memory load involved in task-switching. The results of this research support the contemplation of task demands with respect to the cognitive resources involved when planning or designing for interruptive situations.

Moreover, human performance researchers are becoming increasingly aware of the role of failed prospective memory in work accidents and errors (e.g., Reason 1990). For instance, Einstein et al. (2003) documented the rapid rate of forgetting that can occur in demanding occupations and found that common memory strategies, such as rehearsal, did not alleviate forgetting. These results suggested that tactile cuing is one method that may help alleviate prospective memory demands in certain situations. In particular, the observed differences in primary task behavior in this study may be associated with uncued participants forgetting the decision rule while attending to the secondary task.

In this study, the tactile cues were applied in a manner that simulated a "tap on the shoulder." There are many application domains in which a virtual shoulder-tap might be beneficial. In particular, if tactile transducers were embedded into the back of a seat, then tactile cuing could be employed in a variety of mobile activities such as piloting and driving. For example, aircraft pilots often engage in visually intense activities while simultaneously listening and responding to radio communications. In this environment, tactile cues to important interruptive tasks may lead to fewer errors and faster responses. The same benefits should accrue to stationary activities as well: a variety of command-center tasks involve multi-tasking and frequent interruptions. For example, air-traffic control operators might expect to be able to handle higher volumes of traffic with fewer errors using tactile interruption management strategies.

Of course, some limitations exist in the experiments presented here. While our task environment was more realistic in terms of actual job demands compared to basic laboratory tasks, the environment was not an actual occupational setting. As such, tactile interruption management has not yet been explored using real-life job tasks and real employees who face real consequences. An additional consideration to keep in mind is that we examined the use of tactile cuing over a 30-min interval. Longer periods of use may reveal issues such as differential effects on performance or changes in physical comfort over time.

Nonetheless, tactile cuing appears to be a successful method for managing interruptions amid ongoing performance. The experiment presented here offers a possible explanation for the performance advantages gained via tactile cuing: the ability of the tactile cues to lighten the cognitive resource load by serving as a task-switching reminder. Cued participants, benefiting from an event-based prospective memory task as opposed to a more resource-intensive, time-based task, were thus more cognitively equipped to handle other task demands. Individuals who performed the tasks without the aid of tactile cuing were found to experience considerable costs with respect to speed and accuracy on both tasks. As such, it is clear that the management of interrupting tasks within ongoing performance is not a trivial task. The inability to attend to interruptions without disrupting or neglecting primary task performance can have serious, even life-threatening, consequences in certain task domains. Therefore, tactile interruption management represents a viable method of directing attention and freeing up scarce cognitive resources in interruptive situations in order to enhance overall performance.

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