Using Informative Peripheral Visual and Tactile Cues to Support Task and Interruption Management

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Objective: This study examined the effectiveness of using informative peripheral visual and tactile cues to support task switching and interruption management. **Background:** Effective support for the allocation of limited attentional resources is needed for operators who must cope with numerous competing task demands and frequent interruptions in data-rich, event-driven domains. One prerequisite for meeting this need is to provide information that allows them to make informed decisions about, and before, (re)orienting their attentional focus. **Method:** Thirty participants performed a continuous visual task. Occasionally, they were presented with a peripheral visual or tactile cue that indicated the need to attend to a separate visual task. The location, frequency, and duration parameters of these cues represented the domain, importance, and expected completion time, respectively, of the interrupting task. **Results:** The findings show that the informative cues were detected and interpreted reliably. Information about the importance (rather than duration) of the task was used by participants to decide whether to switch attention to the interruption, indicating adherence to experimenter instructions. Erroneous task-switching behavior (nonadherence to experimenter instructions) was mostly caused by misinterpretation of cues. **Conclusion:** The effectiveness of informative peripheral visual and tactile cues for supporting interruption management was validated in this study. However, the specific implementation of these cues requires further work and needs to be tailored to specific domain requirements. **Application:** The findings from this research can inform the design of more effective notification systems for a variety of complex event-driven domains, such as aviation, medicine, or process control.

INTRODUCTION

In many complex event-driven domains, such as aviation or medicine, operators are faced with the challenge of allocating their limited attentional resources across numerous competing task demands and coping with frequent interruptions of ongoing tasks and lines of reasoning (Sarter, 2007; Woods, 1995). For example, on modern flight decks, pilots need to engage in numerous tasks as they approach their destination airport. They need to brief the approach, program and monitor automated flight deck systems, and communicate with air traffic control. While performing these tasks, they may be interrupted by alerts from the Traffic Collision Avoidance System (TCAS) or by warnings of malfunctioning equipment and are required to prioritize and manage these tasks and interrupting events effectively. Of particular concern are uninformative and unnecessary interruptions of an operator's task set, which affect the efficiency and accuracy of performing both interrupted and interrupting tasks (e.g., Rogers & Monsell, 1995). Interruptions of ongoing tasks are especially problematic when they are immediate and nonnegotiable. A high level of similarity between the interrupting and interrupted task, a high level of complexity of the interrupting task, and a high interruption frequency are also highly detrimental (e.g., Czerwinski, Chrisman, & Schumacher, 1991; Gillie & Broadbent, 1989;

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Speier, Valacich, & Vessey 1997). Given these challenges, there is a need for developing tools that help operators avoid unnecessary interruptions and resulting breakdowns in task performance and management. These breakdowns can take the form of (a) oblivious dismissal (the interruption is missed), (b) unintentional dismissal (the significance is judged incorrectly), and/or (c) preemptive integration (the interruption task is immediately attended to, possibly unnecessarily; see Latorella, 1999). Although the importance of avoiding the performance costs associated with breakdowns in interruption management is widely acknowledged, most existing systems still employ uninformative notifications that fail to support decision making about, and before, reorienting the attentional focus.

To better support interruption management, both the timing and nature of interrupting cues or notifications need to be improved. For example, concerning the timing of cues, operators are known to be more interruptible when they transition between tasks or task sets (Miyata & Norman, 1986). Also, notifications need to be more context sensitive and sufficiently salient without being disruptive (Sarter, 2002; Woods, 1995). They should present operators with partial information about the nature and significance of the pending task or event in an effort to allow them to decide whether and when to shift their attention. One way to achieve this goal may be to model interrupting signals after likelihood alarm displays (LADs; Sorkin, Kantowitz, & Kantowitz, 1988), in which information about the likelihood of the occurrence of an alarming event is encoded into the alerting signal itself. This enables operators to determine the relative urgency and the likely benefit of attending to an alarm, thus improving their attention allocation among multiple tasks and events.

The Cockpit Task Management System (CTMS) developed by Funk and colleagues (e.g., Funk & Braune, 1999) represents a specific example of how informative task-related cues can better support task management in real-world domains. The CTMS provides pilots with information about task state (upcoming, active, terminated), status (satisfactory vs. unsatisfactory performance), and priority. This system has shown to reduce incorrect task prioritization and the number of incomplete tasks during simulated flight deck operations.

One challenge for informative interruption cuing is to display partial information about an interrupting task or event without requiring focused attention, and thus a reorientation away from an ongoing task, to extract the information (Woods, 1995). This challenge may be addressed by presenting the interruption-related information via sensory channels that are currently underutilized in most domains. According to multiple resource theory (Wickens, 1984), this is a promising technique because time sharing is assumed to suffer to the extent that concurrent tasks and monitoring demands share the same resources—most notably, the same sensory modalities. Latorella (1998) demonstrated the effectiveness of this approach in a flight deck simulation study in which pilots' error rate on auditory tasks was much smaller when an interrupting air traffic control instruction was presented visually, rather than auditorily, to avoid resource competition.

Given that operators' foveal visual and auditory channels are heavily taxed in most real-world domains, the peripheral visual channel and touch seem to be particularly promising candidates for presenting interruption cues (e.g., Hopp-Levine, Smith, Clegg, & Heggestad, 2006; Nikolic & Sarter, 2001; Sarter, 2002). These channels allow for the identification of a limited set of characteristic features (such as the brightness of visual cues or the frequency of vibrotactile cues) with minimal processing effort. Peripheral visual cues can be perceived in parallel with foveal visual cues and can serve as effective orientation mechanisms (Posner, 1980). The proximal nature of tactile cues allows them to capture attention reliably, regardless of head or body orientation, and they are not as disruptive as auditory cues (e.g., Jones & Sarter, 2008; Sarter, 2002, 2007; Sklar & Sarter, 1999).

The Present Study

The present study evaluated and compared the effectiveness of informative peripheral visual and tactile cues for supporting task and interruption management in the context of a simulated supervisory control task. More specifically, this research sought to address the following questions: (a) How reliably and accurately can participants detect and interpret peripheral visual and tactile interruption cues while performing a demanding visual task? (b) Do participants make correct decisions about attention switching based on the information encoded in the interruption cues? and (c) How much does the presentation of interruption cues affect performance on the ongoing visual task?

Detection rates were expected to be higher for peripheral visual and tactile interruption cues than for the existing notification scheme, which involves a small embedded visual cue only. The modalities and eccentricities of the experimental cues were chosen to support parallel processing with the ongoing visual task. Because the experimental cues were more clearly separated from other display components than the embedded cue of the existing scheme, they were also somewhat more salient. The interpretation accuracy for experimental cues was expected to depend heavily on the encoding method (i.e., the proper mapping of content-to-signal parameter).

Information regarding the importance of the interrupting task was anticipated to have the strongest effect on task-switching behavior, both intrinsically and because participants were provided with decision rules for this parameter. Finally, ongoing visual task performance in the two experimental conditions was expected to suffer the least in the tactile cue conditions, given that peripheral visual cues may still interfere slightly with foveal visual task processing.

METHOD

Participants

Thirty students from the College of Engineering at the University of Michigan participated in the experiment. Their average age was 25 years (*SD* = 3 years). All participants were right-handed. Participation was voluntary, and participants were compensated $30 for approximately 90 min of their time.

Tasks

The participants played the role of supervisory controller of a simulated water control system in space shuttle operations. They completed two tasks that were representative of the cognitive demands encountered in this domain. In particular, they were responsible for (a) a continuous *arithmetic task* (a representation of the controller's ongoing visual-manual task demands) and (b) a discrete *interrupting task* (handling deviations from the desired water level in the system).

Arithmetic task. Participants evaluated the correctness of a series of simple-integer arithmetic equations, which were presented visually. The four components of each equation appeared one at a time in the following sequence: first, a two-digit operand for 1 s; then an arithmetic operator (+ or −) for 1 s; the second two-digit operand for 2 s; and, finally, an integer solution (which was either the correct or an incorrect sum or difference) for 2 s. Participants had another 4 s to make a response. The full arithmetic equation display and the required button response constituted one experimental trial lasting 10 s. Participants indicated the correctness of the solution by clicking on the appropriate button (✓ when correct, ✗ when incorrect) at the bottom of the screen. A progress bar below the response buttons displayed the time remaining for each trial (Figure 1), and a response error was recorded if time ran out.

Interrupting task. During 50% of arithmetic task trials, participants were notified of an interrupting water control task. They were instructed to use the information encoded in a peripheral visual or tactile notification signal to decide whether, and when, to switch their attention to the interrupting task. The interrupting task, once initiated, replaced the arithmetic task on the screen and required the participant to control the flow of water by clicking on a valve symbol (and thus opening the valve) until a preset water level was reached. With continuous water flow, the water level reached the required height in the holding tank in either 5 s (for the short duration tasks) or 10 s (long duration). Once the task was complete, participants could return to the next arithmetic trial.

Notifications

Three different types of notifications were used to notify participants of a pending water control task: a baseline "uninformative" visual notification and two types of "informative" notifications, presented via either peripheral vision or the tactile modality. The notifications

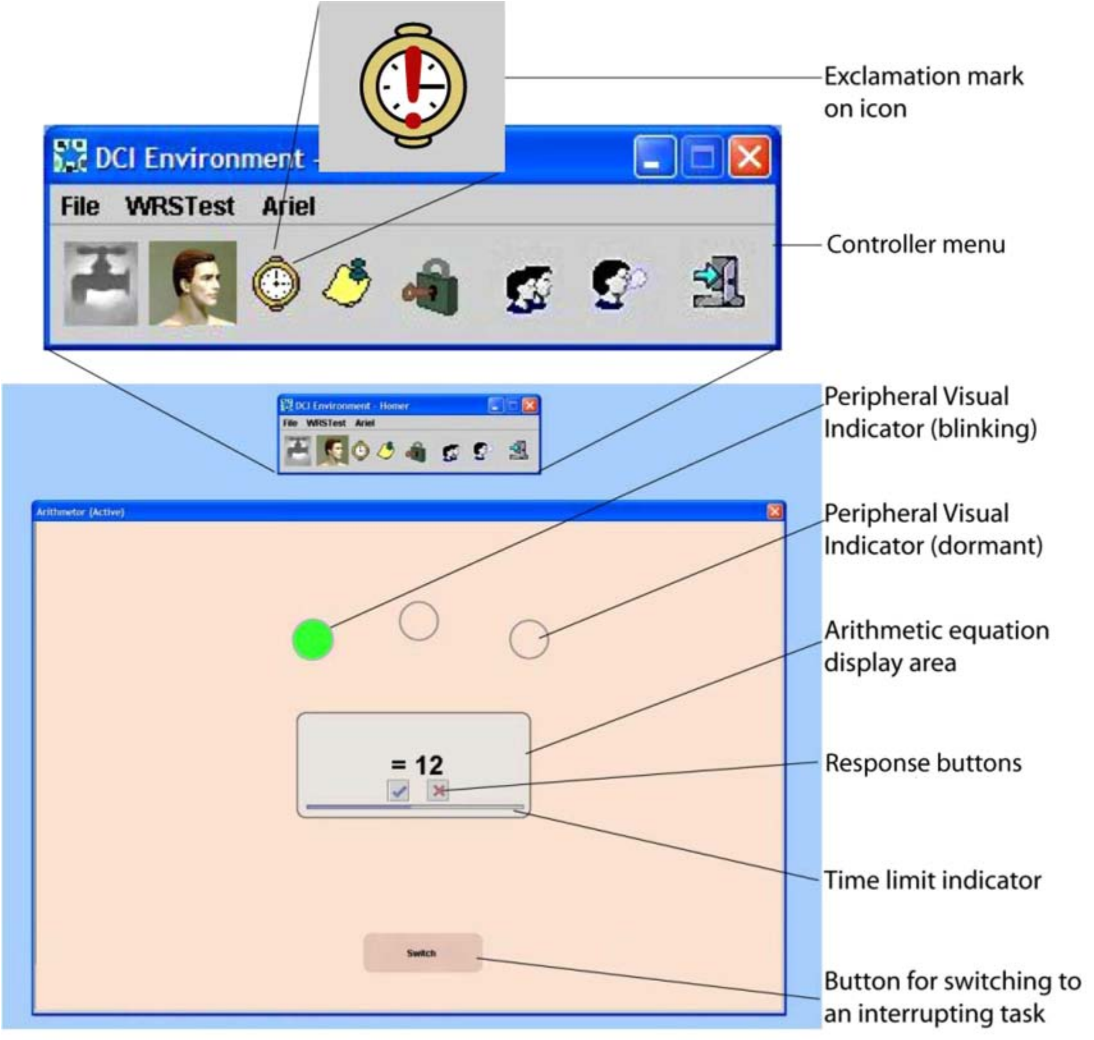

Figure 1. Design and location of baseline visual and peripheral visual interruption cues as well as arithmetic task.

were presented either at the beginning of the arithmetic task trial (coinciding with presentation of the first operand) or 4 s into the trial (coinciding with presentation of the solution).

The baseline visual notification was modeled after the existing notifications used in the Distributed Collaboration and Integration (DCI) system (Martin et al., 2003). It consisted of an exclamation mark that appeared over a clock icon in the controller display to announce a pending interrupting task without providing any additional information about the nature of the task (Figure 1). The exclamation mark remained superimposed on the clock icon for 6 s before disappearing.

The informative peripheral visual notifications were presented in the form of three circles above and approximately 2.5 inches radial distance (6° of visual angle) from the center of the arithmetic task display area (Figure 1). A notification involved one of the circles flashing bright green at a particular frequency for a particular duration, depending on the characteristics of the interrupting task (for details, see the encoding scheme section).

The informative tactile notifications consisted of vibrations that were presented to the participants' fingers using three "tactors": 1" × 1/2" × 1/4" piezo-electric devices (Audiological Engineering Corporation; http://www.tactaid.com/)

that were affixed to a glove. The tactors were positioned directly over the proximal phalanges of the index, middle, and ring fingers. To ensure a consistent spatial mapping, participants were instructed always to rest their hands palms down on the table. Pilot testing was used to select 150 Hz as the operating vibration frequency of the tactors, which is easily perceptible but not uncomfortable. Cue presentation involved periodic activation and deactivation (a regular series of pulses) of one of the three tactors with a specific pulse frequency for a specific duration (for details, see the encoding scheme section).

Encoding scheme. Three types of information about the interrupting task were encoded in the peripheral visual and tactile cues. The *domain* of the interrupting task referred to which one of three water control subsystems required an intervention. This information was communicated by cue location (left, middle, or right). The *duration* of the event referred to the amount of time required to complete the interrupting task (short or long), and it mapped to the duration of cue presentation: Cues were presented for approximately 3 s to communicate a short task duration and approximately 6 s to communicate a long task duration.

The *importance* of the interrupting task (low, medium, and high) was communicated through the characteristic frequency of the cue (flashing of the green circle or vibration pulse frequency). Low task importance was represented by a low pulse frequency (approximately 1 pulse/s), whereas medium and high importance levels were represented by higher cue frequencies (5 pulses/s and 15 pulses/s, respectively). Extensive pilot studies suggested that these cue parameters mapped well onto the relevant information regarding the interrupting task.

Instructions. In the experimental conditions, participants were instructed to immediately switch attention for high-importance interrupting tasks, use their discretion for medium-importance tasks, and never switch for low-importance tasks. No explicit switching instructions were given for tasks of different durations; however, participants were informed that switching for long-duration (as opposed to short) interrupting tasks would have a higher cost on performance in the arithmetic task because the equation display would be hidden for a longer period.

Although noting the domain of the interrupting event was important to addressing the correct subsystem, we did not expect the domain information to affect switching decisions. This information was included primarily to test whether participants were able to extract several dimensions of the signal reliably. In the baseline condition, because no interruption information was encoded in the signal, participants were asked only to note whether a cue was present or not—no task switching was required.

Procedure

After giving written consent to participate in the study, we familiarized participants with the interface, tasks, and required responses during a general training session. Three 15-min experimental sessions followed, each presenting one of the three interruption cues (baseline visual, informative peripheral visual, and informative tactile) in a randomized order. There were 27 arithmetic task trials in the baseline condition and 72 trials each in the informative peripheral visual and tactile cue conditions. Participants completed session-specific training prior to each experimental session. Short breaks (approximately 3 min) between sessions served to minimize fatigue. The entire experiment took a total of approximately 90 min to complete.

Data Collection

Accuracy on the arithmetic task was measured as the percentage of trials in which correctness of the equation was judged accurately. The simulation software discriminated between response errors (which included inaccurate responses and failures to respond within the time limit) and consequential misses (which occurred when participants switched to the interrupting task and did not have a chance to judge the equation). This distinction was important, as misses that were the result of correct decisions to switch to the interrupting task should not reflect as negatively on arithmetic task performance.

Following each arithmetic task trial, participants were asked to complete a short on-screen questionnaire that required them to indicate whether they detected a cue and, if so, to identify the perceived domain, duration, and importance of the interrupting task (for the informative cues). Responses were used to calculate detection rates and interpretation accuracy for each of the three parameters. The questionnaire served to distinguish missed or misinterpreted cues from deliberately ignored interruptions. The participants' decision to switch or not switch to the interrupting task was also recorded by the software.

Experimental Design

The study employed an unbalanced nested design. The main independent variable was cue presence (whether or not a cue was presented during an arithmetic task trial). Within cued trials, the type of interruption cue was varied (baseline visual, informative peripheral visual, and informative tactile), as was the timing of the cue with respect to the onset of the arithmetic equation display (at the beginning or delayed by 4 s). Within the informative cuing conditions (peripheral visual and tactile), three task parameters were varied: interrupting task domain (left, middle, right), duration (short, long), and importance (low, medium, high).

The recorded performance measure for the arithmetic task was the percentage of trials for which an accurate response was given. The dependent measures regarding interruption cuing were detection rate (percentage "detected" responses in the on-screen questionnaire following cue presentation) and interpretation accuracy for each experimental cue parameter (domain, duration, and importance). Finally, the accuracy of participants' task-switching decisions was also recorded in the experimental conditions.

RESULTS

The data were analyzed in repeated-measures ANOVAs, and Bonferroni corrections were used in post hoc analyses (Bonferroni, 1936).

Cue Detection Rate

A significant difference was found between the percentage of cues detected in each cue condition, $F(2, 58) = 9.27$, $p = .0003$. Post hoc pairwise comparisons (with Bonferroni correction) revealed that the baseline visual cues showed lower detection rates (83.3%) than for both the peripheral visual (99.2%), $t(58) = 3.73$, $p = .0004$, and tactile cues (99.2%), $t(58) = 3.73$, $p = .0004$. No difference in detection rate was found between peripheral visual and tactile cues (Figure 2).

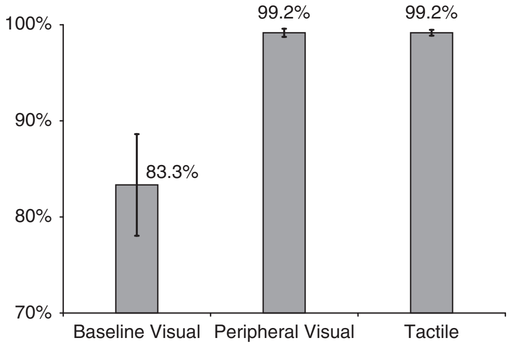

Figure 2. Detection rate as a function of cue modality.

Interpretation Accuracy

The complete set of information encoded in the informative interruption cues (domain, importance, and duration) was correctly interpreted in 70.7% of all cue presentations. The interpretation accuracy for each individual cue parameter differed significantly, $F(2, 58) = 28.65$, $p < .0001$ (Figure 3), with the highest accuracy observed for the identification of domain (95.1%), followed by event importance (88.2%) and duration (83.1%).

Between the two informative cue types, the likelihood of correctly interpreting all three encoded parameters in a cue did not differ. For interpretation of domain information, peripheral visual cues showed a higher interpretation accuracy (96.5%) than tactile cues (93.7%), $F(1, 29) = 8.21$, $p = .0077$. No significant difference was found for the interpretation of task importance or duration (Figure 3).

The timing of the cue with respect to the arithmetic task trials had a significant effect on the interpretation of duration information, $F(1, 29) = 21.862$, $p < .0001$. The interrupting task duration was interpreted with 79.9% accuracy when the cue was presented at the beginning as opposed to 86.4% accuracy when the cue was presented in the middle of a trial. The cue timing did not have an effect on interpretation of the other two cue parameters.

Task-Switching Behavior

For the analysis of task-switching behavior, data from one participant were removed (misinterpreted switching instructions). In general,

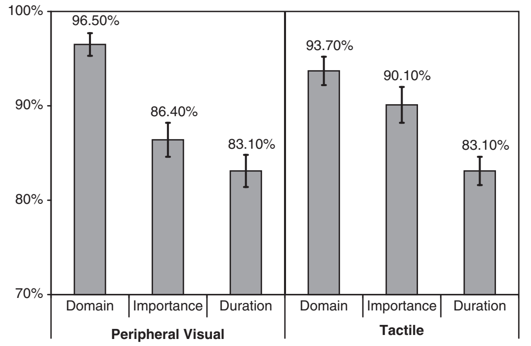

Figure 3. Overall interpretation accuracy for each parameter encoded in informative cues.

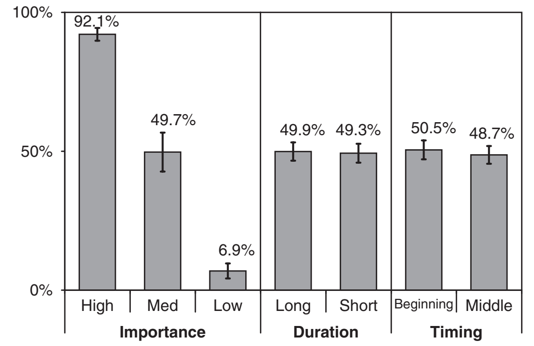

Figure 4. Task-switching rates for each parameter level (correctly interpreted informative cues only).

participants based their switching decisions on task importance, $F(2, 56) = 116.60$, $p < .0001$, with 93.1%, 46.9%, and 1.3% switching rates for high-, medium-, and low-importance interruptions, respectively (see Figure 4). Switching errors are defined as trials in which participants correctly identified the importance of an interrupting task but failed to apply switching rules (always switch for high-importance cues and never switch for low-importance cues). Switching error rates were significantly higher for high-importance cues (6.9%) than for low-importance cues (1.3%), $F(1, 28) = 6.29$, $p = .0182$. No specific switching rules were given for cues with medium importance; therefore, switching error data were not collected for these cues.

Performance on Arithmetic Task

Cue presence, type, and presentation timing had significant effects on arithmetic task accuracy. The peripheral visual condition showed a significant difference in arithmetic performance between cued (trials with a peripheral visual interrupting cue) and uncued trials (93.8% vs. 97.4%), $F(1, 29) = 6.35$, $p = .0175$; see Figure 5.

Cue type also had a significant effect, $F(2, 58) = 6.99$, $p = .0019$, on arithmetic task performance. The baseline condition (in which participants never switched tasks but simply needed to judge the presence of a cue after each trial) resulted in higher accuracy rates (98.1%) than did both the peripheral visual (95.6%) and tactile (96.4%) cues. No significant difference was found between the peripheral visual and tactile cues.

The timing of cue presentation affected arithmetic task accuracies as well, $F(1, 29) = 5.435$,

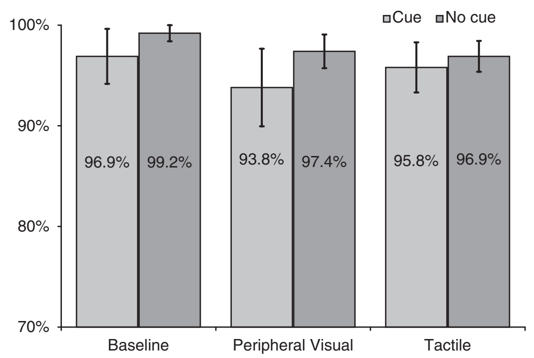

Figure 5. Accuracy on arithmetic task for cued and uncued trials as a function of cue type.

$p = .027$. Lower accuracy was found when cues were presented at the beginning of a trial (86.0%) than when they were presented mid-trial (87.9%).

DISCUSSION

The goal of the present study was to examine the effectiveness of informative peripheral visual and tactile cues for supporting interruption management, a challenge in many data-rich, event-driven domains. Overall, the findings show that both types of informative cues resulted in significantly higher detection rates than in the baseline condition. In fact, both conditions led to almost perfect detection performance. This benefit can be explained for the peripheral visual cues by their higher salience (because of size, color coding, and location relative to primary task display; Nikolic, Orr, & Sarter, 2004; Wickens, 1992). In the case of tactile cues, the use of an otherwise underutilized channel likely resulted in the observed benefit (e.g., Sarter, 2006).

The increase in detection rates as a result of increased salience and redistribution of information to other channels may not be quite as dramatic in some real-world environments as it was in the current experiment (99.2% for both peripheral visual and tactile cues). Participants' relatively stable head position and their visual attentional focus on the center of the screen likely contributed to their near-perfect detection performance for peripheral visual cues. Also, tactile cues were presented to the resting fingers of participants with virtually no incidental vibrotactile noise, which could be present in some real-world domain environments and which could mask these cues to some extent. Finally, the participants were interrupted during 50% of the trials in this experiment to create the number of trials necessary to meet the statistical demands of the study. The performance advantage may vary in domains with lower interruption rates. Still, these conditions are unlikely to entirely account for the observed performance improvements—some domains that stand to benefit from the proposed notifications involve isolated periods of high interruption frequency, and not all involve environmental vibrations or allow for more widely distributed visual attention.

In the majority of cases (70.7% of all cases), participants were able to interpret the information encoded in the interruption cues accurately. Observed differences in interpretation accuracy for individual parameters may be the result of two factors: the need for absolute judgments in some cases and the relative appropriateness of the visual and tactile modalities for conveying certain types of information. Information on task importance and expected completion time required participants to make absolute judgments. By presenting a reference stimulus and thus requiring relative (rather than absolute) judgments, we could improve the interpretability of these parameters.

The task domain, which was encoded spatially, showed the highest interpretation accuracy. This was expected, given the high spatial discrimination capabilities of vision and touch (Intriligator & Cavanagh, 2001; Johnson & Phillips, 1981; Moy, Singh, Tan & Fearing, 2000; Sarter, 2002). In contrast, two forms of temporal encoding were used to communicate task importance (pulse frequency) and expected time to task completion (duration of cue presentation). The tactile modality is better suited for interpreting temporal information than the visual modality (which reflects the trend for accuracy of importance interpretation); however, both vision and touch, compared with audition, require larger differences for reliable temporal, as opposed to spatial, discriminations (Wright, Buonomano, Mahncke, & Merzenich, 1997).

Task-switching behavior. The availability of information about task importance, in combination with decision rules, allowed participants to make more informed and accurate decisions about task switching. Participants almost always (93.1%) switched appropriately when cues announced high-importance interrupting tasks (*intentional integration* in Latorella's [1999] Interruption Management Stage Model [IMSM]). Cases in which participants failed to switch to a highly important task can be explained, for the most part, because they missed or misinterpreted the cue (oblivious and unintentional dismissal breakdowns, respectively, in IMSM; Latorella, 1999). They avoided switching for 98.7% of cues that communicated low importance for the interrupting task (intentional dismissal). Very few participants (1.3%) detected and interpreted the low-importance cues correctly, and yet they incorrectly switched to the interrupting task (preemptive integration). Thus the informative cue designs used in this study seemingly support the desirable responses to interrupting cues, intentional dismissal and intentional integration.

Participants' compliance with task-switching instructions resulted in their improved overall performance, as it allowed them to optimize their performance on the secondary task, minimize unnecessary inattention to the ongoing arithmetic task, and minimize performance decrements associated with the act of switching attention between tasks. These so-called switching costs (e.g., Rogers & Monsell, 1995) have been demonstrated consistently, even for highly practiced tasks, and can increase with task complexity. The switching cost can be significantly reduced if one provides at least partial information about an upcoming task through informative cueing (Meiran, 1996).

The expected time to complete the interrupting task (communicated as duration of cue presentation) appears not to have affected task-switching behavior, even though the amount of time away from the ongoing arithmetic task should affect performance on that task. This lack of consideration may be explained, in part, by the fact that decoding this information was apparently more difficult (lowest identification rate of all parameters; see Figure 3), and thus perceived uncertainty may have limited reliance on this parameter. It is also possible that the relative performance costs associated with time spent away from the arithmetic task may not have been sufficiently clear to participants; therefore, they tended not to base task-switching decisions on this information.

Ongoing task performance as a function of cue type. A trade-off was observed between performance on the primary arithmetic task and the processing of interruption-related information in the informative peripheral visual condition. A similar pattern was observed in the baseline condition between arithmetic task performance and cue detection. In contrast, processing informative tactile cues minimally affected performance on the primary task. The fact that performance on the arithmetic task suffered most when peripheral visual interruption cues were presented may be explained by the onset of proximal visual stimuli capturing and leading to a reorientation of foveal visual attention, which could have interfered with the visual attentional requirements of the arithmetic task (Nikolic & Sarter, 2001). With additional training, participants may be able to suppress this visual reorientation to a larger extent.

In the baseline condition, the lower detection rate for interruption signals and the fact that less processing was required per cue presentation (because they did not encode any information about the interrupting task) may explain the fact that the arithmetic task performance decrement in cue trials did not reach significance.

CONCLUSION

The findings from this study demonstrate that fairly complex informative interruption cues can be used successfully by operators to improve task and interruption management. The reliable detection and interpretation of the peripheral visual and tactile cues, in parallel with the demanding arithmetic task, demonstrates the promise and potential of these cuing methods. Tactile cues may be particularly beneficial for environments that involve primarily tasks that rely heavily on visual processing, such as aviation, process control, or medicine. Special attention should be given to establishing natural mappings between the type and representation of interruption-related information to ensure the highest interpretation accuracy with minimal effort. Further study may explore the additional benefits of informative auditory cuing or cross-modal cuing involving a combination visual, auditory, and tactile stimulus components.

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