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Investigation of multi-modal interface features for adaptive automation of a human–robot system

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Abstract

The objective of this research was to assess the effectiveness of using a multi-modal interface for adaptive automation (AA) of human control of a simulated telerobotic (remote-control, semi-autonomous robotic) system. We investigated the use of one or more sensory channels to cue dynamic control allocations to a human operator or computer, as part of AA, and to support operator system/situation awareness (SA) and performance. It was expected that complex auditory and visual cueing through system interfaces might address previously observed SA decrements due to unannounced or unexpected automation-state changes as part of adaptive system control. AA of the telerobot was based on a predetermined schedule of manual- and supervisory-control allocations occurring when operator workload changes were expected due to the stages of a teleoperation task. The task involved simulated underwater mine disposal and 32 participants were exposed to four types of cueing of task-phase and automation-state changes including icons, earcons, bi-modal (combined) cues and no cues at all. Fully automated control of the telerobot combined with human monitoring produced superior performance compared to completely manual system control and AA. Cueing, in general, led to better performance than none, but did not appear to completely eliminate temporary SA deficits due to changes in control and associated operator reorienting. Bi-modal cueing of dynamic automation-state changes was more supportive of SA than modal (single sensory channel) cueing. The use of icons and earcons appeared to produce no additional perceived workload in comparison no cueing. The results of this research may serve as an applicable guide for the design of human–computer interfaces for real telerobotic systems, including those used for military tactical operations, which support operator achievement and maintenance of SA and promote performance in using AA.

Keywords: Adaptive automation; Situation awareness; Multi-modal interface design; Human–robot interaction

1. Introduction

Many complex systems, like advanced commercial/military aircraft, teleoperation (remote-control robotic) systems and supervisory-control systems for process control operations, incorporate "visually rich" operator interfaces (Sklar and Sarter, 1999). System designers have historically relied on forms of visual feedback to inform operators of changing system states. This approach to display design has led to operating situations that may pose visual sensory channel overload. Visual overload has been defined by human factors research as too much visual information being presented to system operators in a short time (i.e., more information than can be perceived) (Mackworth, 1976). Studies involving simplistic visual search and vigilance tasks have observed negative implications of visual overload, e.g., narrowing the size of the useful field of view ("attentional narrowing") and failure to detect stimuli critical to performance (e.g., Williams, 1982). However, recent research (Sarter, 2000) has summarized that using multi-sensory feedback or multi-modal interface design to cue complex system operators of system-state changes can promote effective human automation

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interaction (HAI) (see Appendix A for a list of definitions of acronyms used throughout this article) in comparison to using visual cues (alone) for the same purpose.

Nikolic et al. (1998) demonstrated that distribution of system feedback across operator sensory channels can significantly improve detection of unexpected system-state changes. They investigated the use of peripheral visual and tactile feedback cues, as compared to focal visual cues, for supporting pilots in maintaining automation mode awareness in a flight simulator when ''uncommanded'' mode transitions occurred. Specifically, a conventional flight mode annunciator was tested along with an enhanced version in which mode transitions were highlighted by changing display background color, and increasing size and luminance. In addition, a display with a large peripheral visual cue (a long stripe underlying transition information) and a tactile display presenting vibrations applied to the wrist of participants with multiple tactors signaling different modes were tested. Workload was varied within-subjects by posing different types of flight tasks (e.g., traffic conflicts, approach revisions) during various phases of trials (take-off, cruise, landing). The peripheral visual and tactile cues significantly increased rates of detection of mode changes over conventional visual presentation. Reaction time to conventional visual cueing of mode transitions was also much longer than times for peripheral visual and tactile cues and, in general, the effectiveness of the experimental cues was less vulnerable to changes in task workload than the conventional flight mode annunciator condition. Nikolic et al. (1998) concluded that focal visual feedback in complex systems control does not adequately support operator attentional guidance to system states and that multi-modal interfaces exploiting the range of human perceptual capabilities need to be developed. They also said that research is needed to identify the most promising implementations of multi-modal interfaces.

Sklar and Sarter (1999) subsequently demonstrated cross-modal cueing on system-state changes to be effective for facilitating HAI (e.g., when the primary task of an operator is visual, there appears to be a benefit to using auditory warnings). They used the same experiment test-bed as Nikolic et al. (1998); however, a larger sample of pilot trainees was tested and different sensory feedback conditions were investigated. Again, pilots monitored for unexpected mode transitions, they verbally announced the transitions they detected and used simulated flight controls to identify the types of transitions. The standard flight mode annunciator (visual-only condition) was used to represent existing cockpit displays. The test conditions included a tactile feedback condition, like that investigated by Nikolic et al. (1998), as well as a bi-modal (dual channel) condition involving both the tactile cue and conventional visual cue. Numerous automation mode transitions were evenly distributed throughout trials. Workload was manipulated by posing pilots with traffic conflicts or engine parameter deviations and they were told all tasks were of equal importance. Sklar and Sarter (1999) found that subjects receiving only the visual cue detected almost 20% fewer automation mode transitions than those receiving the tactile and bi-modal cueing. They also observed that detection performance with modal visual cueing was significantly influenced by flight workload changes, but the test conditions were not. In addition, Sklar and Sarter found that subjects receiving the lone visual cue reacted far slower than subjects receiving modal tactile cueing or bi-modal cueing. Furthermore, reaction times under the visual-only condition were highly influenced by concurrent flight task workload. Another important finding of this study was that pilot identification of the type of automation mode transition was superior under modal visual and bi-modal cueing as compared to tactile cueing. That is, although the detection rate and response time may be better when using an alternative sensory channel, visual cueing was important for correct system-state identification.

In general, these studies show that multi-sensory and redundant, bi-modal cueing can serve to improve operator performance in comparison to visual cues in complex systems control with visually rich interfaces. These approaches to multi-modal system interface design may prevent negative consequences of operator visual overload or lack of mode awareness due to poorly designed system feedback.

1.1. *Interface design for adaptive automation (AA) and situation awareness (SA)*

The recent findings on multi-sensory feedback in complex systems control may be important to the design of human interfaces in adaptively automated systems in which control-mode changes occur over time and warnings of such changes may be useful to operators in preparing to relinquish or resume responsibility for various functions. AA has been defined as dynamic allocation of system functions to a human operator and/or automated controller over time based on operator states and task/contextual information for the purposes of optimizing system performance (Rouse, 1977; Hancock and Chignell, 1988; Scerbo, 1996; Kaber and Riley, 1999). The goals of AA include moderating operator workload and supporting system/situation awareness by facilitating a better match between task demands and operator cognitive resources. Research (Parasuraman et al., 1993; Hilburn et al., 1997) has demonstrated AA to promote performance in both psychomotor and cognitive tasks. Hilburn et al. (1997) also demonstrated AA to produce smaller increases in workload across experimental trials, as compared to fully manual and automated control of a complex cognitive task. However, some prior research on AA and mode awareness in automated systems (Ballas et al., 1991; Sarter and Woods, 1995) has suggested that dynamic function allocations (DFAs) can cause temporary performance decrements, as operators may be unprepared for control-mode shifts, or they may be in the middle of a task when a shift occurs. Operators are typically aware that control-mode shifts will occur in AA systems, but they may not know the exact timing of shifts. Although the use of AA is not identical to complex system operators dealing with unexpected or uncommanded control-mode changes at any point in performance, one solution to mode preparedness problems with AA may be to use sensory cues, like those evaluated by Sarter and others as warnings of system-state changes, to provide operators with advanced notice of pending mode shifts based on predefined approaches to AA.

Kaber and Riley (1999) used terse verbal messaging to inform AA system operators of the need for a control-mode shift based on real-time assessment of operator workload states in a dual-task scenario involving a primary radar-monitoring task and a secondary gauge-monitoring task. Performance in the secondary task was used as an index of workload in the radar-monitoring task and criterion gauge performance levels were set to trigger dynamic allocations of manual and automated control of the primary task. If radar-monitoring workload exceeded the secondary-task (performance) criterion, a message appeared on the gauge display stating that automation should be used in the primary task. A similar message, identifying the need for manual control of the primary task, was presented when operators appeared to be experiencing cognitive underload. The AA of the radar-monitoring task was found to be effective for managing operator workload within a particular range; however, it was observed that the need for control-mode shifts during AA trials was not always immediately salient to subjects due to the visual attention demands of the primary task and the use of visual warnings of DFAs on the separate secondary-task display.

Ballas et al. (1991) used a laboratory simulation of a dual-task scenario involving a target confirmation and classification task along with a tracking task to study the effectiveness of different interface design alternatives, including a direct manipulation style, for presenting AA and to describe the effects on operator performance and SA. AA-induced performance deficits were expected due to the need for operators to adapt to changes in display content and to periodically reorient to different control modes. The direct manipulation interface condition presented graphical displays of the tasks with touch-screen input, as compared to a tabular display with keypad input. Ballas et al. speculated the direct manipulation interface would reduce the cognitive distance between user psychological intentions and actions at the interface and would increase the user's sense of task engagement. This would then ease the transition from one mode of system automation to another. In Ballas et al.'s study, the target classification task was either fully automated or performed manually depending upon the level of difficulty (LOD) of the tracking task. Changes in the state of the target classification task automation were signaled across multiple modalities, including visual stimuli (highlighting display windows with colored line borders) and a beep, to inform operators of when manual control was required. They found that performance (or "SA") decrements occurred during manual system control due to preceding automation of the target classification task. They observed that the direct manipulation interface was superior to a conventional interface for ameliorating adverse performance consequences due to DFAs. However, the cueing of mode changes was not entirely effective for facilitating operator preparation for manual or automated control and ameliorating AA-induced performance and SA decrements. As in Kaber and Riley's (1999) study, it is possible that the interface design features/cues explored in this study may not have made control-mode changes salient to operators. In addition, the cues may not have been sufficiently complex to allow operators to project appropriate future control actions. It is important to note that in Ballas et al. research, SA was not measured directly but inferred based on operator performance.

Related to this last point, little prior work has directly assessed the effect of AA on operator SA and, to our knowledge, no prior research has assessed the effectiveness of cueing of automation-state changes during AA to ensure operator system-state awareness. Kaber and Endsley (2004) used a direct, objective measure of SA to assess the effects of level of complex system automation and AA on operator perception, comprehension and projection in a dual-task scenario involving target elimination and gauge monitoring. They found that the type of automation was critical to operator SA when applied adaptively to the target elimination task; however, the frequency of control allocations and the duration of automated and manual control had comparatively little effect. They found that intermediate-level automation, primarily providing computer assistance in decision functions, and high-level automation had a positive effect on operator SA. The durations of automation cycle times that led to improved SA varied with the level of automation, but generally were shorter for the intermediate level, as compared to high-level automation.

1.2. Multiple-resource theory (MRT) and sensory cueing of adaptive system states

It is possible that the observations on the studies by Kaber and Riley (1999) and Ballas et al. (1991), regarding the effectiveness of cueing control-mode shifts when using AA, may be attributable to attentional resource competition among display information. That is, visual feedback on changes in system states, as part of AA, may not be an effective approach, given an already visually rich control interface. Navon and Gopher (1979) said that separate pools of attention may be allocated to the senses (e.g., a visual attention pool may not be used in perception via other modalities) and that the pools may be of a limited capacity. Wickens (1984) proposed an MRT of attention, which contends that there are multiple pools of attentional resources for processing sensory channels (e.g., vision, audition). He also presented a multi-dimensional representation of attentional resources structured according to modalities of perception and response, stages of information processing and neural codes of information in order to describe potential competition among these dimensions for attention (Wickens, 1992). Wickens said that based on the extent to which any two tasks demand separate, rather than common, resources, along the dimensions of his model, time-sharing would be more efficient and performance of one task would be less likely to influence performance on the other.

The findings of the studies by Sarter and her colleagues support the assertion of MRT that modalities of perception are linked to separate attentional resources and that the distribution of attention across channels leads to improved time-sharing performance. It is expected that MRT may, likewise, be applicable to the design of advanced warning cues on automated-state changes in AA systems with the intention of maintaining operator mode awareness. Sarter (2000) said that multi-modal information representation is one promising avenue toward improving the "communicative skills" of highly automated systems with human operators and that there is a need to examine the advantages of limitations of using various sensory channels for this purpose. It is possible that auditory or bi-modal cueing of DFAs in adaptive systems with complex visual control interfaces may benefit operator performance and SA due to reduced attentional resource competition among perception of cues versus control information, as compared to the use of modal visual cueing of DFAs.

There remains a need to assess the effectiveness of multimodal interface design for use in AA systems to provide operators with feedback on pending DFAs and to mitigate potential performance deficits, as a result of a lack of operator preparedness for changes in the behavior of the system, their role in control, and the available functions and responsiveness of interfaces. There also remains a need to identify what specific types of sensory cues may be best for addressing AA-induced performance and SA problems in visually rich task environments.

1.3. Objective and hypotheses

In this research, we compared the use of modal visual and auditory cues, including icons and earcons, and bimodal cueing using both earcons and icons, on automation-state changes in a high-fidelity simulation of telerobotic system control, including supervisory and manual modes, in terms of human operator performance, SA and perceived workload. We sought to describe the effect of AA and warnings of DFAs on a direct objective measure of operator SA in the simulation.

Based on Ballas et al. (1991) research, it was generally expected that DFAs, as part of AA, could have temporary negative affects on operator SA. We also expected based on prior AA research (Parasuraman et al., 1993; Hilburn et al., 1997) that, overall, AA would yield superior performance to completely manual control and, on the basis of Kaber and Endsley's (2004) research, that AA would lead to better overall operator SA than static, full automation of system control. In addition, we expected AA to yield lower workload than completely manual control of the system.

We also hypothesized, based on Ballas et al. (1991) research, that any cueing of dynamic control allocations as part of AA would support operator SA and improve preparedness for assuming manual control following supervisory control (or vice versa) and subsequent performance. The warnings were expected to make operators aware of the pending control-mode shift and to give them time to prepare for the change in the functioning of the system and the available information as part of the human–machine interface.

Our other major hypothesis on cueing was based on MRT (Wickens, 1984) and the prior research by Sklar and Sarter (1999). We expected cueing through any sensory channel (other than that for which attentional resources were already being used) to be more salient and comprehensible by operators than cueing through channels for which limited attentional resources remained available. Since the system interface for the telerobotic system was visually rich, we expected that complex auditory cues (the earcons) or bi-modal cueing would be superior to modal visual cueing (use of icons) for supporting performance and SA. Finally, we expected that perception of the earcons and icons would not produce significant increases in perceived workload relative to no cueing.

2. Methodology

2.1. Participants

An experiment was conducted in which 32 participants performed telerobot-assisted disposal of simulated underwater mines. Subjects were recruited on a voluntary basis from the NC State University graduate and undergraduate student populations. The average reported age was 21.9 years. There was no control for gender and 11 female and 21 male participants were recruited. Subjects were asked to subjectively rate their virtual reality (VR) experience on a scale from "1" (very low usage) to "5" (very high usage) and the average rating was 1.75. Subject experience in robotic rover control operations was not recorded nor were the background disciplines of the students. The majority were engineering students from industrial engineering, computer science and electrical and computer engineering. It is possible that some of the students may have had experience in mechatronics and rover design and control.

2.2. Experimental design

A 2 LOD (Level of Difficulty—easy and hard) $\times$ 3 cue type (earcon, icon and both) mixed between-within experimental design was used. The LOD was manipulated as a nested variable and cue type manipulated as a crossed variable. The LODs were defined by the amount of clutter in the underwater virtual environment (i.e., obstructions in accessing mines) and the size and salience of mines, and were intended as a manipulation check of the SA and performance effects of AA and cue types across a range of workloads. Half of the subjects were assigned to the easy (or low difficulty) condition and the others performed under the hard (or high difficulty) setting. Each subject used AA and was presented with earcons, icons or both cues on control-mode and task-phase changes in three separate trials.

Telerobot automation-state changes were introduced systematically throughout all AA trials and occurred in conjunction with different phases of the mine disposal, including searching, placing detonation charges and detonating mines. Manual-control periods were scheduled during trials to involve operators in the system control-loop and to promote SA. Automated-control periods, allowing operators to essentially supervise the system, were intended to reduce the perception of overall workload.

AA was implemented based on preprogrammed schedules of manual- and supervisory-control allocations. Half of the subjects exposed to each LOD by cue-type condition experienced a control sequence primarily involving manual control and the remaining half experienced a predominately supervisory-control sequence. In these two AA conditions, subjects either performed: (1) manual searching, followed by supervisory control in placing a detonation charge and then manual control of mine detonation (we used the acronym "MSM" to represent this condition); or (2) supervisory control of the mine search phase, followed by manual control of the place charge phase and then supervisory control of the detonation phase (we used the acronym, "SMS" to represent this condition). This type of approach has been labeled as "model-based" AA in the human factors literature (Parasuraman et al., 1993, 1996; Kaber and Riley, 1999).

Table 1 presents the data collection table for the experiment design. For each LOD by cue type by control-mode sequence settings, eight subjects were used as repeated measures.

Several control conditions were also investigated through the experiment, including a completely manual telerobot-control mode, a fully automated-control mode and an AA condition with no automation-state cueing whatsoever. The conditions were used to evaluate the various hypotheses on operator performance and SA. Twelve of the 32 participants from the primary experiment were assigned to a completely manual-control group, another 12 were assigned to the fully automated-control condition, and the remaining eight subjects experienced AA with no cueing of state changes. The number of subjects assigned to the various control conditions was not balanced due to cost and time constraints on the project. The control conditions were presented in random order with the other AA trials as part of the experiment.

In total, each subject completed four trials presenting icons, earcons or bi-modal (combined) cues alerting of pending task-phase and automation-state changes, or no cues at all. During all experimental trials subjects completed two mine disposals.

2.3. Task

The experiment task was based on a realistic tactical Navy mission with an enhanced teleoperated ordnance disposal system. A VR model of an underwater environment (ocean littoral region) was developed for the experiment, including oceanography, rock beds, plant life and mines. Four different types of virtual mines were created and littered throughout the virtual environment. The VR also included a model of an underwater telerover (see Fig. 1), resembling a prototype Navy unmanned underwater vehicle. The rover was capable of moving along the floor of the virtual environment in search of mines and could collide with other virtual objects (e.g., sea life).

Under the manual-control mode, subjects controlled the behavior of the rover by using a standard mouse controller and giving specific verbal commands to an experimenter for execution using a keyboard. The mouse was used to

Table 1
Data collection table for primary experiment

Level of (task) difficulty											
Low						High					
Subjects											
1, …, 8; 25, …, 32						9, …, 24					
Cue type											
Auditory		Visual		Both		Auditory		Visual		Both	
Adaptive automation strategy											
SMS	MSM	SMS	MSM	SMS	MSM	SMS	MSM	SMS	MSM	SMS	MSM
$n=8$	$n=8$	$n=8$	$n=8$	$n=8$	$n=8$	$n=8$	$n=8$	$n=8$	$n=8$	$n=8$	$n=8$

Fig. 1. Exocentric view of virtual environment and telerover.

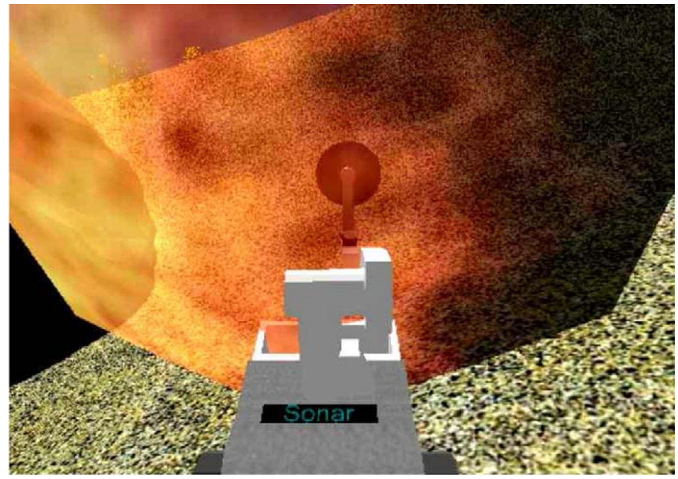

Fig. 2. Rover in detonation phase.

Table 2
Steps in mine disposal task

Phase 1: Search—locate and drive to mine.

Phase 2: Place detonate charge:
- Activate magnetic gripper.
- Move robot arm to charge storage bin and pick-up charge.
- Move arm to reach mine.
- Move rover to place charge on mine.

Phase 3. Detonate:
- Move rover back, away from mine.
- Move arm to aim sonar at detonation charge.
- Activate sonar to detonate charge.

drive the rover by controlling direction and speed, and voice commands were used to control the movement of a six degree-of-freedom manipulator arm mounted on the rover and to select various end-effectors for the phases of the task, including a magnetic gripper and sonar emitter. Beyond this, the mouse buttons could be used to release detonation charges from the gripper, activate the sonar and to select different viewpoints of the rover from simulated cameras mounted on the vehicle. The viewpoints included egocentric and exocentric perspectives on the manipulator arm and end-effector. They also allowed for viewing of an "active tool" display on top of the rover. A Wizard of Oz like technique was used to effect subject voice commands because they donned a head-mounted display in order to view the VR and could not look at the computer system keyboard. The supervisory-control mode involved full automation of all task functions with intervention by the human operator for troubleshooting or resolving system errors.

The specific steps of the teleoperation task, which were automated or manually controlled, are presented in Table 2. While immersed in the virtual environment, subjects searched for mines by driving the rover and using the camera views. Once they found a mine, and the rover moved within a minimum distance of it, subjects controlled the robot arm and magnetic gripper to place a detonation charge on the mine. This task required complex and accurate positioning of both the rover and robotic arm. Finally, subjects disposed of the mine by detonating the charge using the sonar. This required moving the rover to a safe distance from the mine and manipulating the arm to aim the sonar emitter at the charge. When the sonar was activated, the charge and mine exploded (see Fig. 2).

2.3.1. *Earcon and icon design*

The earcons and icons were integrated in the VR to assist subjects in completing the steps of the mine disposal by notifying them of pending changes in the mode of system automation and task phases. Earcons are auditory cues defined by many musical dimensions (timbre, rhythm, pitch, etc.) to convey complex messages (Blattner et al., 1989). Blattner et al. (1989) said that earcons have several advantages over conventional auditory warnings, including being easily recognizable/distinguishable and learnable, as well as not posing startle problems often associated with warnings without musical properties or problems in interpretation of meaning. She also recently observed (Blattner, 2000) that earcons may be more effective for conveying critical task/system states than speech warnings in environments in which conversations are on-going among operators or operators issue verbal commands that could be confused with speech warnings. (Verbal cues (e.g., speech or text) were not examined in this study because of potential interference with voice commands for robot arm control.) Contemporary work (Brewster, 1998; Blattner, 2000; Brewster et al., 2001) has also developed earcon design guidelines and investigated the use of earcons for cueing automated system states. Brewster (1998) demonstrated earcons to improve HAI by cueing multiple modes of automation in "smart houses".

In the current study, compound earcons encoding the task-phase and automation-state changes were played for subjects through headphones as part of the head-mounted display and through computer speakers for the experimenter. Two families of earcons were developed for this purpose (automation states and task phases), which were distinguishable specifically by timbre (voice or tone quality). The individual earcons were combined to form the compound earcons. During experiment trials, task-phase changes were presented first (i.e., search, place charge, detonate) followed by the cue for the control-mode change (i.e., manual or supervisory control), with only a slight pause between them.

Icons indicating task-phase and control-mode changes were overlaid on top of the virtual environment imagery and were located in the lower left portion of the screen in the parafoveal area of vision (i.e., within 10–30° of operator focal vision on the rover; Kieras and Meyer, 1997). Although Nikolic et al. (1998) were successful in warning operators of complex system-state changes with peripheral visual cues (i.e., cues 60° or more from the center of vision; Kieras and Meyer, 1997), objects in the peripheral field of view are only detected by changes in luminance or motion, and the actual shape, color and (consequently) meaning of complex objects may not be clear because acuity is much lower than in foveal vision. Parafoveal cues, allowing for operator discrimination of shape and detail, can be used to convey much more complex information than peripheral cues. The icons we used were semi-abstract and incorporated concrete analogies to automation states and task phases. Fig. 3 presents the icons for the experiment, including an image of a hand to represent manual control, an image of an eye to represent supervisory control, an image of a magnifying glass to represent searching, an image of a detonation charge to represent the charge placement phase and an image of a bomb to represent the detonation phase of the task.

All icons and earcons were presented within approximately 10 s of task-phase and automation-state changes. The presentation time was consistent across the visual and auditory cues. All the earcons and icons were displayed for approximately 4 s. Each earcon lasted about 2 s in duration and compound earcons, cueing both automation-state and task-phase changes, took 4 s. The earcons and icons were only presented once for each set of system state and phase changes.

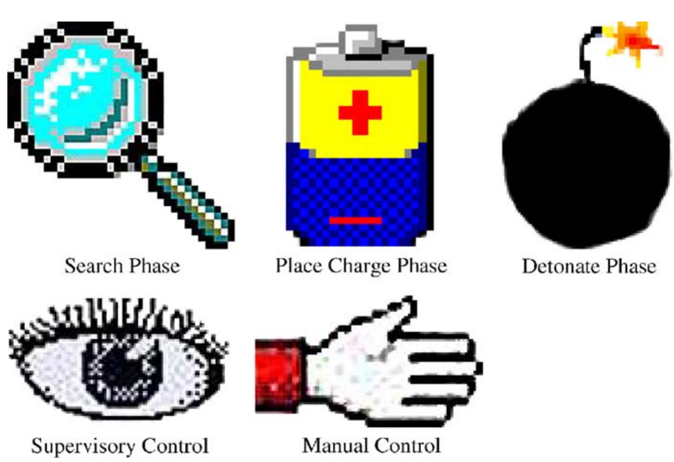

Fig. 3. Icons used to cue automation-state and task-phase changes in experiment.

2.4. *Response measures*

The response measures recorded during the study included time-to-task completion (TTC), number of task performance errors (e.g., incorrect manipulator tool selection, incorrect voice commands, etc.), subjective ratings of perceived workload, and a direct, objective measure of SA. Workload was rated by participants using the NASA task load index (TLX) (Hart and Staveland, 1988). Subsequent to task training, participants ranked six workload demand components (mental, physical, temporal, effort, performance and frustration) in terms of importance to the task and they rated all components at the end of each test trial.

The situation awareness global assessment technique (SAGAT) (Endsley, 1995) was used to assess operator perceptual knowledge (Level 1 SA) and comprehension of the task environment and system states (Level 2 SA), as well as operator ability to project future states (Level 3 SA). In a teleoperation scenario, an operator's internal situation model must represent the elements of the remote work environment and states of the remote robot for effective decision-making and performance to occur. This information is typically acquired through a local system control interface. In the mine disposal simulation, the state of the remote work environment dictated the stages of rover operation. For example, if a mine was detected and approached by the rover, the task progressed to the "place charge" phase. Through perception of the environment (Level 1 SA) the operator needed to be able to project this (Level 3 SA) and to adequately comprehend and respond to system states (Level 2 SA). Therefore, states of the environment had implications for SA on task-phase changes, as did the occurrence of the cues.

As part of the SAGAT, three simulation freezes were conducted during trials in order to administer questionnaires on operator internal situation models. The freezes were evenly distributed across the phases of the simulated mine disposal in all trials and they occurred at random within predetermined windows of time, with an equal number occurring between 10 to 45 s before and after task-phase and automation-state changes. During each freeze, the system display was blanked and operators responded to nine queries, including three queries targeting each level of SA. Some examples of queries include: "What mode of automation is the simulation running under?"; "What type of mine is closest to the rover?"; "Do you have the correct tool activated to perform your current phase?"; "Is the arm of the rover close enough to place a charge on a mine?"; "What is the next step of the task?"; "What tool should you select next?". There was no time limit for answering queries. The percentage of correct operator responses to queries on Level 1, 2 and 3 SA and a total SA score were determined based on data recorded on the actual state of the task by the VR computer system. After a quiz was completed, the telerobot-control simulation resumed immediately from the point at which it was frozen. No feedback was provided to operators based on the SAGAT results.

2.5. Procedures

Experimental training and testing was distributed across 2 days for each subject. We initially conducted hearing and vision tests with all subjects. The training and test regimen for the study included:

(1) Practice in a basic teleoperation task simulation.
(2) Earcon and icon training.
(3) Familiarization with the underwater VE.
(4) Practice in the simulation using the head-mounted display.
(5) Training on SA quizzes and workload rating.
(6) Testing in four trials.

In specific, the subjects observed supervisory control of the rover in a mine disposal. They were provided with an explanation of rover voice commands, and were allowed to detonate a mine under manual rover control. During the earcon training, an experimenter played and explained each possible earcon to subjects. The subject was then allotted 5 min to study the earcons, subsequent to which a short quiz was administered to ensure learning. Proficiency with the earcons was defined as correctly identifying four-of-five test earcons. If a subject did not learn the earcons successfully during the first test, he or she was allowed another 5 min to study. A second quiz was then administered and if the subject could not meet the proficiency requirement, he or she was dismissed from the study. Two subjects out of a total of 34 subjects recruited for the study were dismissed because they were unable to reach the earcon training proficiency.

At the beginning of the second day, participants were refreshed and quizzed on the earcon and icons. With the head-mounted display, they observed one mine detonation in supervisory-control mode and they were allowed to detonate one mine under manual control. They were refreshed on the task and voice commands and trained on the SA quizzes and workload ratings to occur during, and at the close of, trials. Directly subsequent to this, participants completed the test trials.

2.6. Data analysis

Each trial yielded a single observation on TTC, number of errors, and the NASA-TLX workload measure. The data analysis included a composite workload score and the ratings of individual demand components that were highly ranked by subjects at the beginning of the experiment (mental demand, performance and effort). With respect to the SA measure, each trial and the simulation freezes produced three observations on each of the three levels of SA and the total SA score. As part of the data analysis, the SA data were also coded with a variable indicating whether the freeze occurred before or after a control-mode shift.

The performance, SA and workload measures were subjected to two-way analysis of variance (ANOVA) with LOD and cue type included in the statistical model as between- and within-subjects predictors. With respect to the performance measures, only the analysis of TTC is presented here. The pattern of results on the error counts across LODs and cue type essentially mimicked the pattern of results on TTC (mean error counts for auditory cueing were lower than for bi-modal cueing, but bi-modal cueing produced a shorter average task time than auditory cueing). In the analyses involving the control conditions, one-way ANOVAs were used with either the form of automation or cue type included in the model as the predictor variable. The analysis of operator SA before and after DFAs also involved a one-way ANOVA with the timing of the SAGAT freeze (before or after a control-mode change) as the independent variable. If significant effects were identified based on ANOVA results ($p<0.05$), post hoc analyses were conducted using Duncan's multiple range test with an α level of 0.05. (We elected to use Duncan's test because it has been observed to be sensitive for identifying truly significant differences among condition settings and, provided the ANOVA is significant, the method is considered to be conservative, SAS, 1990.)

3. Results

Related to our first hypothesis, analysis of the AA trial data demonstrated that we were successful in reproducing temporary operator performance and SA deficits due to DFAs, or control-mode shifts from manual to supervisory control (and vice versa), as Ballas et al. (1991) had suggested. An ANOVA was conducted to compare operator SA before and after task-phase and automation-state changes and revealed significant differences in the total SA score ($F(1,188)=15.67$, $p=0.0001$), and operator comprehension (Level 2 SA) ($F(1,188)=6.30$, $p<0.0129$) and projection of system states (Level 3 SA) ($F(1,188)=17.91$, $p<0.0001$). Fig. 4 presents the mean percent correct responses to Level 1, 2 and 3 SA queries before and after automation-state changes as part of AA trials with cueing of DFAs. The lines presented in the graph above the bars for the condition means serve to class (or define) groups of means that are not significantly different, when the lines appear at the same level. Lines with different patterns represent different post hoc analyses. In general, SA was always worse after a system-state change ($p<0.05$). We observed a similar pattern of results for the no-cueing condition, but the overall levels of

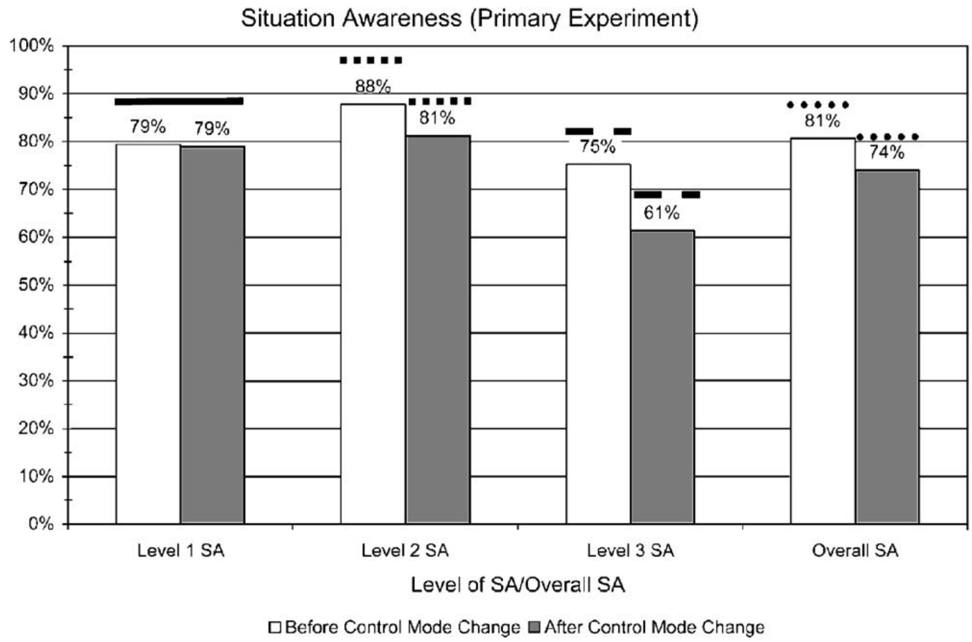

Fig. 4. Mean SA (across cue-type conditions) before and after control-mode changes during AA trials (only).

operator SA and, accordingly, performance were different. We will say more about this later.

In general, the LOD manipulation check was successful. TTC was consistently and significantly longer ($p<0.05$) for subjects in the ''high'' difficulty group (mean mine disposal time = 1167 s) than subjects in ''low'' difficulty group (mean = 815 s). In the following sections, we focus on the performance, SA and workload effects of the automation and cue-type conditions, and any significant tests on LOD are briefly reported. In each section, we first present comparisons of data on the AA trials versus the manual and fully automated-control conditions to provide an assessment of the effectiveness of the AA in terms of each response measure. Secondly, we present the comparisons of AA trials, involving cueing of control-mode changes, with trials involving no cueing whatsoever for each response measure. (Data on the manual and fully automated-control conditions are not included in these comparisons.) Finally, we present the results of the primary experiment revealing the affects of the LOD and cue-type manipulations on operator SA, performance and workload during only the AA trials with automation-state cueing.

3.1. Performance

An ANOVA was conducted to compare the completely manual- and supervisory-control conditions with the AA conditions in terms of operator performance. Results revealed a significant effect of the type of control ($F(3,21) = 12.56$, $p<0.0001$) on TTC. Fig. 5 presents the mean TTC under each mode of automation of the simulation (including the control conditions) when cueing was used. (The acronyms in Fig. 5 presented along with the AA condition means identify the sequence of rover

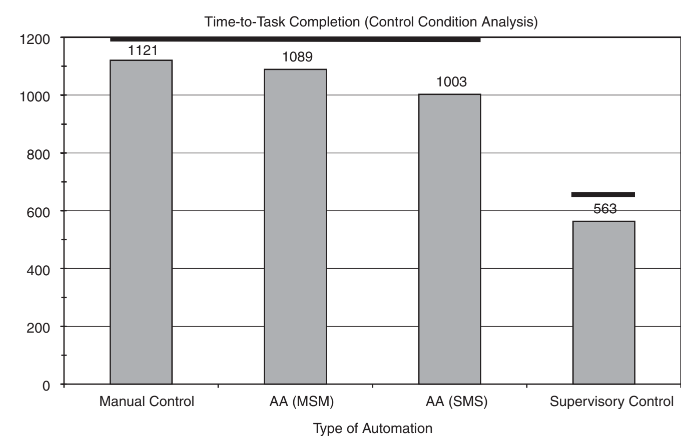

Fig. 5. Mean TTC for each mode of telerobot automation.

automation states as part of the test trials (i.e., manual–supervisory–manual, ''MSM'') or supervisory–manual–supervisory, ''SMS''.) We hypothesized that AA would yield better performance than completely manual control. In general, TTC decreased with increasing levels of task automation and, on average, AA involving primarily supervisory control appeared to produce shorter task times than the completely manual mode. However, this difference did not prove to be statistically significant. According to Duncan's multiple range test, supervisory control (fully automated control of the rover with human monitoring) produced significantly lower ($p<0.05$) TTC than all other modes of operation. (Again, the lines presented in the graph, which span across the tops of the bars for condition means, at the same level, indicate the condition means are not significantly different from each other.)

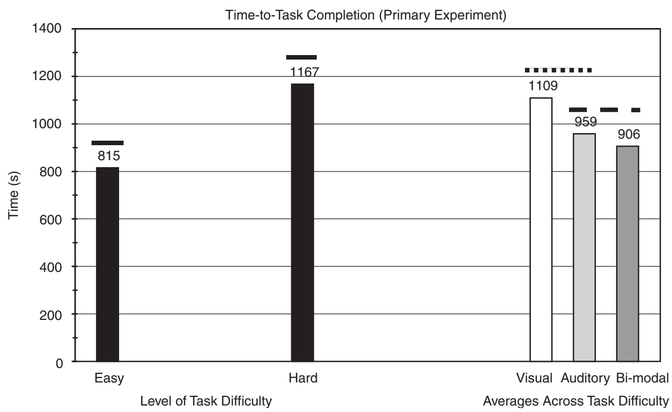

Fig. 6. Mean TTC for each LOD group and each cue-type condition.

A second ANOVA was conducted to make comparison of task performance under the no-cue control condition versus AA conditions involving cueing. We hypothesized that any cueing would lead to operator performance improvements. Results revealed a significant effect on TTC ($F(1,7) = 6.09$, $p = 0.043$) with bi-modal cueing (mean = 600 s) producing the shortest times compared with no cues (mean = 842 s) ($p<0.05$). There were no significant differences among the modal cueing conditions and the no-cueing control condition in terms of TTC.

For the main comparison of the specific cue types, a 2×3 ANOVA on TTC revealed the manipulations of LOD ($F(1,30) = 13.99$, $p = 0.0008$) and cue type ($F(2,60) = 3.29$, $p = 0.0442$) during the AA trials to be significant in effect. Fig. 6 presents the mean TTCs for each LOD group and for each cue-type condition (earcons, icons, both). (The data used in this analysis did not include the no-cueing control condition.) As previously mentioned, TTC was longer for the high LOD group. On the basis of MRT, we hypothesized that the earcons or bi-modal cueing would be better for performance than visual cueing. Visual cueing of task-phase and control-mode changes appeared to degrade performance, as compared to auditory and bi-modal cueing across LODs. Duncan's multiple range tests confirmed that TTC was significantly greater ($p<0.05$) when task-phase and control-mode changes were visually cued, as compared to bi-modal cueing. As in Figs. 4 and 5, the lines presented in Fig. 6 that span across the tops of the bars for condition means (at the same level) reveal the means that are not significantly different from each other. Lines with different patterns represent different post hoc analyses. There was no significant interaction between the task difficulty condition and the cue condition indicating that the differences in performance due to cue type were equally likely regardless of the changes in task load. In general, visual cueing was always worse than bi-modal cueing.

3.2. Situation awareness

An ANOVA comparing the manual- and supervisory-control conditions with the AA conditions revealed operator ability to project future system states (Level 3 SA) to be significantly affected by the control mode ($F(3,113) = 2.82$, $p = 0.0423$). We hypothesized that AA would facilitate better operator SA than static full automation. Means breakout using Duncan's multiple range tests revealed that AA primarily involving manual control produced operator SA (mean percent correct responses to queries = 75%) comparable to that observed under manual system control (mean = 79%) and fully automated control with human monitoring (mean = 78%). However, percent correct responses to SA queries were lower in AA trials primarily involving supervisory control (i.e., full automation of the search and detonate tasks with intervening manual control of the place charge task) (mean = 61%) compared to all other conditions ($p<0.05$). The pattern of results suggested that SA was dictated, in part, by the extent of automation of the task and whether subjects had to keep track of dynamic control allocations (as in the AA trials).

An ANOVA comparing operator SA in the no-cue control condition versus all other cueing conditions revealed significant effects of cue type on operator perception of system status ($F(1,37) = 5.27$, $p = 0.0275$). We hypothesized that any cueing would lead to better operator SA. Post hoc tests indicated bi-modal cueing to produce significantly higher ($p<0.05$) percentages of correct responses to SA queries (mean = 82%) than no cues (mean = 67%). However, there were no significant differences among the modal cueing conditions and no-cueing control condition in terms of SA.

For the main comparison of cue types, a 2×3 ANOVA on the LOD and cue-type manipulations as part of the AA trials indicated subject perception of system status (Level 1 SA) to be significantly affected by the cue type ($F(2,188) = 3.39$, $p = 0.0359$). Fig. 7 presents the mean percent correct responses to SA queries for each cue type across LODs. Based on Wickens' (1984) MRT, we hypothesized that the earcons or combination of earcons and icons would support operator SA more than visual cueing. The general trend of the data was for SA to

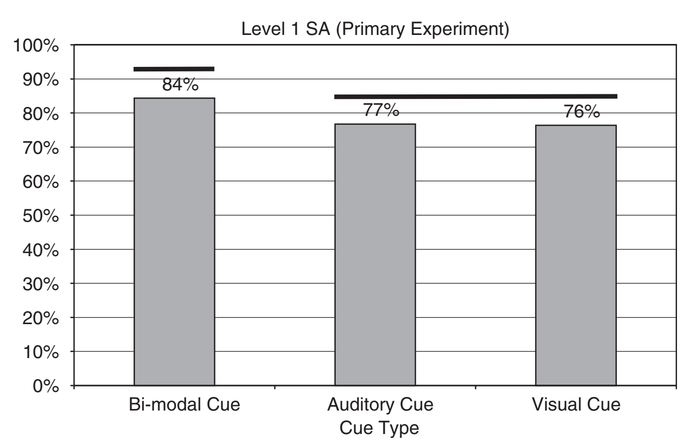

Fig. 7. Mean percent correct responses to SAGAT queries for each cue type.

Table 3
Means on operator SA under completely manual or fully automated control with cueing of task phases

SA response	Before task-phase change (%)	After task-phase change (%)	Significance level
Level 1	81	77	$p > 0.05$
Level 2	88	81	$p < 0.05$
Level 3	79	68	$p < 0.05$
Overall	83	75	$p < 0.001$

increase with cross-modal or bi-modal cueing. Duncan's multiple range tests confirmed that SA was superior during trials involving bi-modal cues in comparison to modal cues ($p < 0.05$).

Beyond this, we conducted an analysis of observations on operator SA before versus after task-phase and control-mode changes during all trials under the completely manual and fully automated-control conditions. Our objective was to determine whether SA decrements might also be occurring in trials in which no DFAs were scheduled and only task-phase changes occurred. An ANOVA revealed significant decrements in operator comprehension (Level 2 SA) ($F(1,113) = 5.14$, $p = 0.0252$) and projection (Level 3 SA) ($F(1,113) = 5.12$, $p < 0.0255$) of system states after (control-mode/task-phase) changes occurred across all cue types. Likewise, total SA scores were found to be significantly lower ($F(1,113) = 10.21$, $p = 0.0018$) after task/system-state changes than before. Table 3 presents the means for the various SA responses before and after task-phase changes, unaccompanied by automation-state changes.

In general, SA decrements were not expected in the control condition trials, absent of DFAs. However, this evidence indicates that decrements also occurred due to the task-phase changes, which were scheduled at the same times in trials as control-mode changes (during AA conditions). To some extent, these findings may explain the persistence of SA decrements under the AA conditions with cueing of DFAs. That is, some portion of decrements in those trials may be attributable to the need for operators to think about, and orient to, new phases of the task. Related to this, it is also possible that modal auditory and bi-modal cueing of DFAs were not effective for mitigating such problems because the time for operators to mentally transition from the use of a mental model for supervisory control of the system to a manual-control mental model (and vice versa) may have been greater than the time between the advanced warning of the control-mode shift and the shift itself (approximately 10 s for all cues). Furthermore, even when an operator is warned of a pending mode shift, they must continue to rely on the mental model for the current mode of control until the shift actually occurs. Thus, if there is no explicit means of transitioning control provided through the interface, the operator may be forced to reorient to a new control mode at the moment the DFA occurs (depending upon the complexity of the system).

3.3. Workload

An ANOVA comparing the manual- and supervisory-control conditions with the AA conditions revealed operator ratings of perceived effort to be significantly influenced by the type of automation ($F(3,21) = 3.09$, $p < 0.05$). Duncan's multiple range tests indicated that fully automated control of the rover with human monitoring produced significantly lower ($p < 0.05$) ratings (mean effort score = 29) than all other modes of operation (AA (MSM) mean = 53; manual-control mean = 46; AA (SMS) mean = 44). Related to our hypothesis on the workload effect of AA, it was also observed that the AA condition primarily involving supervisory control was not perceived as being significantly different from manual control in terms of overall effort; however, AA predominately involving manual control was perceived as worse. The overall pattern of results on effort reflected the extent to which supervisory control was used in trials. It is possible that operators perceived a higher demand as a result of manual control combined with the need to track mode changes as part of the adaptive conditions.

An ANOVA making comparison of cueing conditions with no cueing whatsoever revealed no significant differences ($p > 0.05$) in the composite NASA-TLX score. Our hypothesis based on Nikolic et al. (1998) research was that the cueing conditions would not lead to perceptions of additional cognitive load in comparison to no cues. Icons and earcons appeared to produce overall workload levels comparable to no cueing. Workload results through analysis of ratings of mental demand for only those conditions presenting cues also revealed icons and earcons to not significantly differ ($p > 0.05$) in cognitive demand.

For the main comparison of cue types, a 2×3 ANOVA on the LOD and cue-type manipulations as part of the AA trials indicated a marginally significant effect of cue type on subjective ratings of effort ($F(2,60) = 2.98$, $p = 0.0582$). The trend of the workload data was for higher levels of effort associated with processing visual cues in comparison to earcons, but differences among conditions means did not achieve our significance criterion.

4. Discussion

The results of this study demonstrated AA to yield slightly better average performance than manual control and to facilitate SA comparable to manual control involving the operator in the system loop and supervisory control offloading the operator to observe system states. These are important findings because the completely manual-control condition required operator involvement in the system control-loop throughout test trials; therefore, their level of awareness of the state of the teleoperation system should have been high. With respect to SA under the completely supervisory-control mode, as previously noted, this form of automation served to offload operators to merely observe the states of the system. Consequently, it would have been possible for them to develop high levels of SA, particularly Level 1 SA (perception). Although the results of the control condition analyses generally supported the use of fully automatic (supervisory) control for enhancing performance and reducing workload, the results do not consider the long-term implications of operator out of the loop performance problems, such as skill decay (cf., Shiff, 1983), on the ability to address error conditions or system emergencies. This must be considered carefully in applying automation to complex systems, such as telerobots.

As we expected on the basis of previous research, the TTC was greater when visual cueing of automation-state changes was used in conjunction with the visually rich task interface. The use of auditory cues appeared to facilitate superior performance, as compared to visual cueing. In general, these results are in agreement with MRT (Wickens, 1984). Furthermore, the results were in agreement with Sklar and Sarter's (1999) research demonstrating reduced perceptual-task time with redundant, bi-modal coding of cues. It is possible that bi-modal cues may have drawn greater operator attention upon presentation of the auditory stimulus and then provided information equivalent to visual cues for supporting operator SA. This observation is in line with Sklar and Sarter's finding that visual cues remain important for correct system-state identification when cross-modal cues are used as warnings of mode transitions in complex systems.

Although the earlier observation we made on the relation of AA and SA is generally promising from a systems design perspective, decrements in SA attributable to DFAs, as part of AA, were observed under cueing conditions. It appears that some AA-induced decrements in SA may be pervasive across cue types; however, our findings do indicate that advanced warnings of DFAs can raise the overall level of operator SA and, consequently, performance. SA was never as good under the no-cueing condition, as the best SA achieved with either modal or bi-modal cues. Total SA under AA conditions with cueing of DFAs was approximately 80% accurate. The best overall SA under AA circumstances, without cueing of control-mode changes, was only 75% accurate.

In comparing the specific cueing conditions, we found that redundant, bi-modal cueing of DFAs appeared to best support operator SA, in particular perceptual knowledge, in comparison to modal visual or auditory cueing of system-state changes. It is important to recall that the visual stimulus, as part of the bi-modal cues investigated in this experiment, was a parafoveal cue within 10–30° of operator focal vision. As previously noted, the advantages of parafoveal cues over peripheral visual cues, which have been explored in earlier research (Sklar and Sarter, 1999), include increased salience of stimuli to operators and they allow for presentation of more complex cues involving size and shape changes (and not simply luminance changes). This type of detailed visual cueing along with an auditory warning may help to limit performance problems associated with temporary SA decrements at the time of task-phase or system control-mode shifts.

The lack of significant differences in perceived workload among the cueing and no-cueing conditions was in agreement with the results of Nikolic et al. (1998) demonstrating the effectiveness of cross-modal warnings of uncommanded system-state changes to not be influenced by concurrent (flight) task workload and for the utility of visual warnings, as part of a visually rich interface, to be limited by on-going tasks. The trend we observed for higher perceived workload with the presence of visual cueing of DFAs was also in line with these results and, in general, MRT. Our results indicate that it is possible to design unobtrusive earcons and icons (for presentation in parafoveal vision) that do not compete with on-going tasks as part of a teleoperation mission.

It is important to note that in the context of real-world teleoperation systems, false alarms in cueing of automation states and automation failures may occur. This could lead to a lack of operator preparedness for control-mode shifts and degraded follow-on performance. The results of the present study may not hold under conditions in which automation-state cues may be erroneous or when telerobot automation errors occur.

5. Conclusions

In general, multi-sensory feedback or multi-modal interface design for cueing operators into dynamic system states, as part of AA, appears to be of substantial benefit to performance and it may significantly improve operator awareness of system states in comparison to modal feedback or interfaces providing no cueing whatsoever. The superiority of the multi-modal cueing condition in this work holds only for the earcons and icons that were custom designed as part of the visually rich telerobot-control interface. The specific results on modal and bi-modal cueing of dynamic control allocations may serve as an applicable guide for the implementation of AA in complex systems and the design of multi-modal communications through system interfaces to support operator SA and promote overall performance. This work identified bi-modal (auditory and visual) cues as being superior for facilitating mode awareness in teleoperator control and performance when using a visually rich system interface in comparison to no cueing whatsoever. The findings of the experiment could be critical to facilitating effective HAI in adaptive systems for which a single task error could mean complete mission failure.

We also demonstrated that a model-based approach to AA, involving dynamic allocations of manual and supervisory control, of strategic cognitive task functions can facilitate levels of operator SA comparable to those observed under manual-control conditions (when an operator is continuously involved in a system control-loop) and to yield, on average, better performance with no additional cost in workload. This observation is, however, strongly dependent upon the efficiency of the autonomy of the telerobot system. In the present study, it was possible for the autonomous control algorithm to outperform the human operator in the teleoperation. If automation as part of adaptive system control is generally worse than a human operator, it is possible that AA could yield performance results worse than completely manual control. However, historical research with different types of dynamic control task simulations has also demonstrated AA performance to be superior to completely manual control (e.g., Parasuraman et al., 1996).

The present work adds to the developing corpus of research on the SA implications of AA (cf., Kaber and Endsley, 2004) in complex systems. Specifically, a direct, objective measure of SA was used to describe changes in operator perception, comprehension and projection of system states as a result of dynamic control allocations.

5.1. Future research

The main question that remains to be explored in future studies is, how can we completely eliminate temporary SA and performance decrements associated with dynamic control allocations, as part of AA. The issues that we think are of importance include the timing of cues on system-state changes and the availability of interface/control mechanisms for transitioning from one mode of automation to another. There is a need to establish optimal timing of various forms of cueing of automated system-mode changes and task-phase changes to promote effective HAI in adaptive systems. We also think there is a need to develop transitional modes of control in adaptive systems that facilitate smooth (mental model) changeovers for operators from the use of high-level automation to periods of manual control (and vice versa). Such modes might integrate functions of supervisory control with operator manual responsibility for others, and they could be employed until the operator indicates (through a system interface) readiness for a complete control changeover. One concern with this approach would be additional cognitive load imposed on the operator as a result of thinking about the changeover.

Finally, applications of telerobot technology are expanding to teams of distributed human operators collaboratively controlling and coordinating teams of unmanned vehicles and manipulation systems, possessing varying degrees of autonomy, in tactical and civil operations. In such scenarios, it may be critical to invest in a better understanding of multi-modal interface design (Sarter, 2000) for facilitating HAI to address more complex missions than would occur in single-operator-single-robot systems. There is a need for team research experiments to investigate the effects of various modalities of command and feedback (two-way communication) among automated controllers and human operators of telerobotic systems for coordinated performance.

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Appendix A. Definitions of acronyms

AA	Adaptive automation
ANOVA	Analysis of variance
DFA	Dynamic function allocations
HAI	Human automation interaction
LOD	Level of difficulty
MSM	Sequence of manual control, supervisory control and manual control
MRT	Multiple-resource theory
NASA-TLX	NASA task load index
SA	Situation awareness
SAGAT	Situation awareness global assessment technique
SMS	Sequence of supervisory control, manual control and supervisory control
TTC	Time-to-task completion
VR	Virtual reality

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