Supporting Situation Awareness Through Robot-to-Human Information Exchanges Under Conditions of Visuospatial Perspective Taking

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The purpose of this study was to test the effects of robot-to-human information exchanges on the development of human situation awareness under differing levels of visuospatial perspective taking and the effect of situation awareness on the quality of human assistance provided to a robot. Fifty-six male participants with ages ranging from 18 to 29 (M = 18.89, SD = 3.41) were included in the analysis of the results. The results showed that if robots can increasingly support a human’s understanding of when assistance is needed, they will be better able to provide that assistance. When spatial information was added to robot-to-human information exchanges, representing that spatial information in global-relative reference frames was more beneficial than representing that information in reference to the human’s view of the environment.

Keywords: human-robot interaction, situation awareness, information exchange, visuospatial perspective taking

Introduction
The long-term vision of military robotics is one in which robots will serve as integrated members of dismounted soldier-robot (SR) teams working in complex battlefield environments and collaborating with soldiers to achieve common goals. Robots will be expected to extend the skills of soldiers and to engage in behaviors that resemble those employed in high-performing human-human teams. Autonomous capabilities will allow robots to complete separate but interdependent tasks without constant, direct oversight from soldiers. However, although future military robots will be more autonomous than today’s largely teleoperated robotic systems, they will not perfectly replicate soldiers in reliability (i.e., ability of the robot to avoid failures and complete tasks alone) or intelligence (i.e., robot’s ability to be aware of its failures and make appropriate adjustments), at least in the near term. Instead, robots will possess a subset of capabilities that will be leveraged to perform a wide variety of work, not unlike the ways in which working animals are utilized in human-animal teams (Phillips, Ososky, Swigert, & Jentsch, 2012; Phillips, Schaefer, Billings, Jentsch, & Hancock, 2015). Just like working animals, military robots will be skilled at performing some tasks and limited in performing others, and as a result, will require occasional human assistance to complete tasks.

Human assistance provided to robots
Because robotic teammates in the near future will be limited in reliability, the SR team will need a means to recover from robot failures or deal with robots that are unable to complete their tasks.
alone. In the near term, robotic competence for completing team tasks will not match human competence. Although the robotics and machine learning communities are working to develop human-level competence, robots still have difficulty with many skills that come naturally to humans. For example, robots have difficulty with perceptual tasks in cluttered or complex terrain (Nguyen-Huu, Titus, Tilbury, & Ulsoy, 2009), and robots have difficulty resolving ambiguity in their high-level perceptual tasks (Fong, Thorpe, & Baur, 2003).

For many missions, a robot may need assistance resolving ambiguity or perception difficulties. Take, for instance, a scenario in which a robot is sent to surveil the back door of a building. Once the robot has navigated to the back door of the building, the soldier may need to configure the robot’s view of the back door, or in the event of multiple back doors, specify the door to surveil. Researchers Fong, Thorpe, and Baur (2003) described that assistance offered by humans can often make a big impact on and for robots, “frequently, the only thing the robot needs to get out of difficulty and to perform better is some advice (even a small amount) from a human” (p. 255). However, as they currently exist, robots are not equipped to know when assistance from a human is needed or when they are performing poorly. This is especially problematic as robot performance tends to be brittle when faced with novel applications or dynamic environments (McCarthy, 1995; Novianto & Williams, 2009). For future SR team tasks, there will be a need to reconcile the requirement for humans to provide assistance to robots with limitations in the ability of robots to know when they need assistance and, subsequently, to ask for it.

Information sharing

One method of facilitating awareness of robot performance is through robot-to-human information sharing. Schuster and Jentsch (2012) stated that robots can be active participants in the development of a soldiers’ situation awareness (SA) through their communication and coordination with team members. Under conditions in which robots possess high autonomy and self-sufficiency, however, the constant need for communication between robots and humans is removed. As a consequence in those situations, the operations of robots can become opaque to human teammates. When a robot periodically exchanges information with a person, that person can stay apprised of the status of the robot and its surrounding environment. Such interactions become a means to foster situation awareness of the activities of other team members (Salmon, Stanton, Walker, & Jenkins, 2009).

In addition, in the human-human teamwork literature, communication marked by altering, updating, and providing information about the state of the team’s task completion has been associated with the emergence of SA among team members. A study by Parush et al. (2011) observed surgical teams performing ten open-heart surgeries to investigate the communicative processes by which SA was developed and maintained within surgical teams. The researchers focused on speech acts in which situation-related information was shared among the team. Results revealed that the largest proportion of speech within the team was spent announcing information (i.e., reporting on a value, state, or action taken) or directing, instructing, and/or requesting members to report actions regarding the state of the equipment and procedures undertaken by individual members. These results suggest that the majority of speech within these teams was intended to build awareness of the state of the patient and processes undertaken by individual team members. Similar results have been found for teams working in energy distribution systems as well (Salmon, Stanton, Walker, & Jenkins, 2009). Salmon et al. noted that when team members share information in the form of status updates and alerts, SA-relevant information is exchanged between members and SA among the team is updated and maintained. Thus, the communication patterns that successful human-human teams employ to maintain SA may be a suitable starting point for helping soldiers maintain SA regarding the functioning of their robotic teammates, which can also be used to aid robots when needed.

Prior approaches

Many of the prior approaches to facilitating operator SA regarding robots (i.e., the perception of the robot’s location, surroundings, and status; the comprehension of their meaning; and the projection
of how the robot will behave in the near future; Yanco & Drury, 2004).¹ have centered on developing and improving control and display devices that serve as the medium for information exchanges between the robot and the human operator. Specifically, research has focused on evaluating various displays and interfaces for supporting situation awareness for the remote teleoperation of robots. In most instances of teleoperation, robots provide a continuous view of their actions via video data that is sent back to operators as a continuous stream of information (Yanco & Drury, 2007).

This method of robot-to-human information exchange is taxing on the human visual and information processing systems, which can lead to human performance issues. These include loss of peripheral perception of the environment due to a limited field of view (FOV); loss of the ability to orient the robot in the environment due to unawareness of the robot’s inclination and shape; loss of depth perception which leads to an underestimation of distance to and size of targets (Chen, Haas, & Barnes, 2007); cognitive fatigue, and inability to control the robot alone (Burke & Murphy, 2004). As a result, it becomes very difficult for operators to build and maintain SA regarding the robot and its operating environment. Murphy and Burke (2005) described that for teleoperated robots, roughly 60% of communications between operators were related to building and maintaining SA, and that almost half of the time on task was dedicated to operators trying to determine what they were seeing through the eyes of the robot, as opposed to spending time actively maneuvering the robot. Further, the use of display-based interfaces for information exchanges between robots and humans requires operators to be “heads down” while continuously monitoring the robot (Brown, Gray, Blanco, Juneja, Alberts, & Reinerman, 2011). Even if changes to the display device reduce workload on the human visual system and improve SA regarding the robot, the use of the device still requires operators to continuously keep their hands and eyes on the device when teleoperating the robot. This type of ‘heads down’ operation can reduce the effectiveness of a squad of soldiers, as the robot operator is not able to keep ‘hands on’ his/her weapon and ‘eyes on’ the environment. Consequently, the operator requires protection from one or more of his or her other teammates (Brown et al., 2011). The intended design of future military robotic teammates aims to eliminate the need for constant monitoring of the robot (Army Research Laboratory [ARL], 2012).

At the same time, the elimination of a visual display device presents a significant hurdle for facilitating operator SA regarding the robot, as many of the findings on improving SA regarding the robot through the information exchange devices will not be applicable to future military robots. Video display devices for continuous monitoring will largely be absent. Thus, there exists a gap in the research concerning means to facilitate operator SA regarding the robot when constant, continuous monitoring of the robot is removed. Under the current model of robot teleoperation, SA regarding the robot is improved by maps, sensor overlays, and other contextual details that are synthesized and presented to operators through the visual display. With the requirement that devices largely be removed, there is a need to investigate other means to facilitate SA regarding the robot, which will ultimately enable operator intervention in robot tasks.

Integration of visuospatial perspective

One potential solution is to improve/augment information that is transferred to humans directly from the robot. Meaning that, if it is possible for the robot to synthesize and augment information about the environment via its own internal processing, that information can be transmitted in its augmented form directly to the human teammate (e.g., via text, speech, tactile, or other appropriate

¹ Briefly, the most widely accepted definition of situation awareness is a three-level model given by Endsley (1995a) defined as, “The perception of elements in the environment within a volume of time and space (level 1), the comprehension of their meaning (level 2), and the projection of their status in the near future (level 3)” (p. 36). Situation awareness regarding the robot is Endsley’s (1995a) three-level model applied specifically to the robot.
medium) in small increments rather than a continuous stream of data. For example, the ability of the robot to interpret and integrate situational views and transmit that information to human partners could aid the human in developing SA regarding the robot and its operating environment. The ability to apply visuospatial perspective taking (VPT) (Piaget & Inhelder, 1956 as cited in Flavell, 1992) to information exchanges could influence the development of SA regarding the robot.²

In general, VPT refers to the ability to imagine how a scene looks from varying viewpoints. VPT is said to have two levels; level 1 refers the ability to discern whether an object in the environment will be visually accessible to an outside observer. Level 2 refers to the ability to discern not only whether said object is visually accessible but also how that object will look from an outside observer’s point of view (Flavell, 1992). In prior research studies, VPT has been associated with spatial skills that have been linked to the development of SA in individuals (Carretta, Perry, & Ree, 1996; Endsley & Bolstad, 1994), as well as performance in human-robot teams (Chen, 2011; Fincannon, 2013).

To illustrate what this integration might look like, one can imagine a mission in which a soldier and a robot are working together to screen the entry/exit points of a building. The soldier and robot begin the mission in a common starting position. The soldier issues a command to the robot to surveil the building of interest, and both teammates begin to navigate to their respective observation posts (OP); the robot’s OP is near the back door, whereas the soldier’s OP is near the front door. While the robot is navigating to the back door of the building, the robot sends an alert message to the soldier that there is an abandoned car located along its intended route to the back door of the building. This notification is an exchange of level 1 SA information regarding the robot (i.e., information that is related to the perception of relevant features of the robot’s environment as described by Endsley’s, 1995a, 3-level model of SA). The exchange includes inferences concerning the visual accessibility of objects to others (i.e., level 1 VPT). The robot has made an alert to the soldier based on its knowledge that the soldier does not have visual access to the car located along the robot’s navigation route.

Due to the obstruction in the original path, the robot then alerts the soldier that its path planner has suggested a new route to the OP. This notification is an exchange of level 2 SA information (i.e., information that is related to the meaning of relevant features of the environment; Endsley, 1995a), as the position of the car necessitates a new route. This exchange also includes level 1 VPT.

Although the previous update is likely useful to the soldier, the robot may be able to foster a deeper level of SA in the soldier (i.e., level 3 SA, the projection of future states), if the robot is able to transform the information from level 1 visuospatial perspective information to level 2 visuospatial perspective information. Level 2 visuospatial perspective refers to the ability to infer how objects appear differently from different spatial points of view (Flavell, 1992). For instance, due to the obstruction in the robot’s original path, the robot could alert the soldier that its path planner has suggested a new route to the OP and that the path will take the robot to its left around the building; in the direction of the soldier’s right hand side (level 2 VPT). This additional information would provide the soldier with a means to make a projection about the future path of the robot. For instance, the robot’s suggested path would place the robot in direct line of sight of one of the main doors of the building. Realizing this new path may place the robot at risk of being detected and possibly destroyed, the soldier can make a correction to the robot’s path (see Fig. 1).

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² VPT in this context is unlike other conceptualizations of perspective taking outside the psychological literature (e.g., narratology, philosophy, cognitive science, and neuroscience). For a review of perspective taking across domains, see Streater, Elias, Bockleman Morrow, and Fiore (2011).
With the previous alert, the robot has provided the soldier with additional visuospatial processing and made a projection about relevant SA information on behalf of the soldier’s unique point of view of the operating environment. This information aided the soldier in making an appropriate correction to the robot’s planned path. Many missions envisioned for near-future human-robot teams are highly spatial in nature. Understanding the spatial layout of important features of the urban environment will be critical to the team’s success. Sending alerts and sharing information that enhances spatial understanding should ultimately be more meaningful for the human and aid in the completion of the team’s tasks.

Significance, purpose, and hypotheses

Although, in the near term, the cognitive capabilities and perceptual skills of robots will not match their human counterparts, this does not mean that robots cannot serve as valuable assets in future SR teams. In fact, a study by Schuster (2013) showed that even unreliable information provided by a robot can help a human develop SA when the ability of the human to do so unaided is poor. Further, U.S. Army doctrine specifies that “Every soldier is a sensor” on the battlefield (United States, 2008). Thus, human teammates will expect robots to contribute to operator SA by sharing information in an effective, proactive way (ARL, 2012; Schuster, Keebler, Zuniga, & Jentsch, 2012). A robot exchanging information with additional VPT processing is a complementary means to leverage the unique capabilities of humans and robots by taking advantage of a robot’s ability to easily perceive and process multiple points of view and of the soldier’s ability to utilize shared...
information to develop SA, and intervene when needed. For the near term, there is a need to understand how information sharing capabilities of robots can be leveraged to provide useful gains in operator SA.

The purpose of this study was to test the effects of information exchanges provided by a robot on the development of SA in a human partner under differing levels of VPT and consequential effects on the quality of human assistance provided to a robot. The following hypotheses were given:

H1: More robot-to-human information exchanges should be associated with better SA regarding the robot than fewer robot-to-human information exchanges.

H2: Robot-to-human information exchanges that include level 2 VPT information will lead to higher levels of SA regarding the robot than robot-to-human information exchanges that include level 1 VPT information.

H3: Higher levels of SA regarding a robot will be positively associated with better human assistance provided to a robot.

Method

Participants

This study was comprised of 56 male participants with ages ranging from 18 to 29 (M = 18.89, SD = 3.41). Participants were recruited from the undergraduate research pool in the University of Central Florida’s Psychology Department, and they were provided with course credit in exchange for their participation.

Experimental task

Participants in this study were informed that their mission was to work together with a simulated robot on a reconnaissance and surveillance mission to complete several objectives. Participants were told that their role would be to (a) play the part of a soldier in a simulated soldier-robot team, (b) use information exchanges from the robot (described below) to keep track of the robot’s movement in the simulated environment and answer questions regarding the robot’s movement and location, (c) provide assistance to the robot, and (d) pay attention to how quickly the robot was completing its objectives. In this team, the robot was responsible for (a) navigating a waypoint path through the simulated environment and (b) periodically providing information exchanges with the soldier regarding the buildings located at each waypoint, as well as other status information concerning its navigation. Throughout each mission, the waypoint movement of the robot was scripted, and the participant was not responsible for maneuvering the robot.

During the course of each mission, the robot periodically shared information exchanges with the participant concerning its movement through the environment. Specifically, once the robot reached each waypoint, it made a waypoint status update. This update included information that identified the buildings located on either side of the robot (e.g., “There is a church on one side and a residence on the other”), as well as other status information (i.e., the robot’s status as stopped, the estimated time to reach the end of its route, and its estimated percentage of the planned route the robot had completed). Fig. 2 presents an example of a status update that was given by the robot each time the robot reached a waypoint along its path.
Figure 2. Example of a robot-to-human information exchange in the form of a waypoint status update, given when the robot was stopped at a waypoint.

The robot also periodically exchanged information concerning the direction of its movement through the environment in the form of traveling status updates (e.g., “Heading north toward the next waypoint”). Fig. 3 provides an example of a traveling status update. Participants were responsible for using the information contained in these status updates (both waypoint and traveling) to keep track of the robot’s location in the environment, answer SA-related questions, and to provide assistance to the robot (described in more detail below) when needed.

Figure 3. Example of a robot-to-human information exchange in the form of a traveling status update, given while the robot was maneuvering between waypoints.
Change detection task

While receiving status updates from the robot, participants were also asked to engage in a dual task in the form of a change detection task. The change detection task was used to provide an active task for the participants to complete while the robot was navigating through the virtual environment and sending status updates. Performance on this task was used to examine the effects of the various experimental manipulations on dual-task performance. The event rate, signal saliency, and number of icons present at the start of each mission were used to maintain a medium level of workload for the experimental task.

Design, testbed, and study conditions

The study employed a within-subjects design where all participants completed four experimental missions (see Table 1). The order in which participants completed each mission was determined using a Latin squares design. The Latin squares design ensured that each mission occurred in each possible relative position in the study (i.e., 1st mission, 2nd mission, 3rd mission, 4th mission) with equal frequency and without necessitating all possible permutations of the order of completion of the missions (i.e., 24 possible permutations of the 4 missions).

Each mission was completed in simulation using the Mixed Initiative Experimental Testbed (MIX), a simulation platform for studying human-robot interaction (see Barber, Leontyev, Sun, Davi, Nicholson, and Chen, 2008). The MIX simulation displayed a simulated robot operator control unit (Fig. 4). Robot-to-human information exchanges were presented to participants in the upper right hand portion of the screen, the change detection task was completed in the lower half of the screen, and the upper left-hand portion of the screen contained a mission timer, also referred to as a countdown clock. Participants did not have access to the robot’s real-time location in the environment or the robot’s first-person view of the environment.

Figure 4. Screenshot of the operator control unit in the MIX simulation testbed.
1. **Waypoint status updates (A) condition.** Under the Waypoint status updates (A) condition, the participant playing the role of the soldier received status updates when the robot reached each waypoint. The participant received status updates that reported on the buildings located on either side of the robot, the robot's status as stopped, its estimated time to reach the end of its route, and its estimated percentage of the planned route the robot had completed (see Fig. 2). In this condition, participants received 7 waypoint status updates throughout the course of the mission.

2. **Waypoint status updates (B) condition.** Under the Waypoint status updates (B) condition, the robot stopped at and sent roughly twice as many waypoint status updates as the Waypoint status updates (A) condition. In this condition, participants received 13 waypoint status updates throughout the course of the mission.

3. **Level 1 VPT context.** Under the Traveling + waypoint status updates level 1 condition, participants received status updates concerning the direction of the robot’s movement (e.g., “Heading East toward the next waypoint”) in addition to the status updates given at each waypoint. This resulted in receiving information exchanges from the robot approximately 13 times throughout the course of the mission. Traveling status updates with level 1 VPT presented information concerning the direction the robot was traveling through the environment in global-relative, cardinal and/or intermediate directions (e.g., heading north, south, or southwest).

4. **Level 2 VPT context.** Under the Traveling + waypoint status updates level 2 condition, participants received status updates concerning the direction of the robot’s movement in addition to the status updates given at each waypoint. This resulted in receiving information exchanges from the robot approximately 13 times throughout the course of the mission. Traveling status updates with level 2 VPT presented information concerning the direction the robot was traveling through the environment as clock face directions that were relative to the soldier’s position in the environment (e.g., heading 3 o’clock) in addition to global-relative, cardinal, and/or intermediate directions. Clock face directions were chosen to denote level 2 VPT, because level 2 VPT represents the ability to infer how objects appear to be situated in an environment in relation to an outside observer’s view of those objects, as well as the outside observer’s position in reference to those objects. Clock face directions communicate relative bearing in reference to the direction the navigator in a team/crew/ship is facing. Therefore, level 2 (i.e., clock face) information provided by the robot, is soldier-relative as opposed to global or robot-relative, and such a method allows the robot to provide information to the soldier that is specific to how the soldier would perceive environmental information. In addition, clock face coding is a method for communicating relative bearing/navigation information that is standard in military aviation, seafaring, and land navigation contexts (United States; 2009). Thus, using clock face directions maintains consistency with terminology that is familiar to the people intended to be interacting with military robots in the near future. Fig. 5 provides examples of the two types of traveling status updates used in the Traveling + waypoint level 1 condition and the Traveling + waypoint level 2 condition.

![Status: Maneuvering
Heading: North
Toward next waypoint](image1)

![Status: Maneuvering
Heading: 6 o'clock, West
Toward next waypoint](image2)

**Figure 5.** Examples of level 1 and level 2 VPT traveling updates.
Table 1. *Table of within-subjects conditions. All participants completed missions numbered 1, 2, 3, and 4.*

<table>
<thead>
<tr>
<th>Mission #</th>
<th>Conditions</th>
<th>Description of mission</th>
<th>Description of robot-to-human information exchanges</th>
<th># of exchanges/updates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Waypoint status updates A</td>
<td>Participant receives an update when the robot reaches a waypoint.</td>
<td>Updates report on the buildings located on either side of the robot, the robot’s status as stopped, its estimated time to reach the end of its route, and its estimated percentage of the planned route it has already completed.</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Waypoint status updates B</td>
<td>Participant receives an update when the robot reaches a waypoint. Robot stops at more waypoints than in Waypoint status updates A condition.</td>
<td>Updates report on the buildings located on either side of the robot, the robot’s status as stopped, its estimated time to reach the end of its route, and its estimated percentage of the planned route it has already completed.</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>Traveling + waypoint level 1</td>
<td>Participant receives updates from the robot while it is traveling between waypoints in addition to receiving updates when the robot reaches each waypoint.</td>
<td>Updates report the direction of the robot’s movement at level 1 VPT (e.g., “Heading east toward the next waypoint”).</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>Traveling + waypoint level 2</td>
<td>Participant receives updates from the robot while it is traveling between waypoints in addition to receiving updates when the robot reaches each waypoint.</td>
<td>Updates report the direction of the robot’s movement at level 2 VPT (e.g., “Heading east, at 3 o’clock toward the next waypoint”).</td>
<td>13</td>
</tr>
</tbody>
</table>

*Overhead map*

For each mission, participants were provided with a copy of an overhead map of the urban environment in which the simulated team was operating. This map listed each building located in the environment and depicted the waypoints that comprised the robot’s intended path through the environment, including the start and end points of the robot’s route. The location and configuration of the buildings listed on the map did not change between missions. Fig. 6 depicts an example of an overhead map provided in one of the missions.
Measures

SA regarding the robot. Throughout each mission, the participant was periodically probed with questions associated with level 1, level 2, and level 3 SA regarding the robot. Following the SAGAT method of SA measurement (Endsley, 1995b), each question represented an objective measure of SA with only one correct answer. The simulation briefly paused, the participants’ screen temporarily blanked, and participants were asked to respond to SA questions that corresponded to the three levels of SA regarding the robot.

At each pause, three SA questions (one for each level) were presented from a bank of possible SA questions (see Table 2 for the bank of possible SA questions and the frequency with which each question was asked throughout the study). Each question was intended to measure one level of the participants’ awareness regarding the robot, environmental, and task features. To minimize the likelihood that participants would memorize both the question being asked and when it would be asked, two steps were taken. The first was to develop a bank of different SA questions with different formulations of level 1, level 2, and level 3 SA questions. Second, the presentation of SA questions was randomly timed throughout each mission.

Participant SA regarding the robot was probed twice during each mission. The scoring of the responses to the SA questions was as follows: correct responses to level 1 SA questions = 1 point, correct responses to level 2 SA questions = 2 points, and correct responses to level 3 SA questions = 3 points. Points acquired for each SA question were summed to provide an overall total score for the SA probe event (minimum possible score = 0, maximum possible score = 6). Then, scores for each SA probe event were summed to provide an overall SA score for the mission (minimum possible score = 0, maximum possible score = 12). Finally, SA scores were summed across the four conditions to provide an overall SA regarding the robot score for the experimental phase of the study (minimum possible score = 0, maximum possible score = 48).
Table 2. Bank of SA regarding the robot questions and the frequency with which each question was asked throughout the study.

<table>
<thead>
<tr>
<th>SA regarding the robot</th>
<th>Question</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1: Perception</td>
<td>Where is the robot?</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Between which two buildings is the robot currently located?</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Is the robot near any sensitive buildings?</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>How much time is remaining on the countdown clock?</td>
<td>2</td>
</tr>
<tr>
<td>Level 2: Comprehension</td>
<td>Thus far, has the robot veered from its planned waypoint path?</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Is the robot at the assigned waypoint?</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Has the robot’s waypoint path, thus far, come into contact with any sensitive buildings?</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>In what direction would the robot need to travel to get back to (waypoint number)?</td>
<td>2</td>
</tr>
<tr>
<td>Level 3: Projection</td>
<td>At its current rate, is the robot going to reach the end of its path in the time remaining?</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>If the robot proceeds to the next waypoint, will it encounter any sensitive buildings?</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>If the robot travels East for 2 blocks from its current location, will it encounter any sensitive buildings?</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>If the robot heads toward 3 o’clock for two blocks from its current location, will it encounter any sensitive buildings?</td>
<td>1</td>
</tr>
</tbody>
</table>

Providing assistance to the robot. While the robot was moving through the environment, it occasionally veered from its planned waypoint path by navigating to a different waypoint or series of waypoints. Performance on the measure of providing assistance to the robot was operationalized as the participants’ ability to re-route the robot back to its planned path. When the simulation paused to ask SA regarding the robot questions, participants were asked an additional question, “Based on its current location, does the robot need to be rerouted?” If participants answered yes, then they were directed to a map on which they could physically draw a route for the robot to navigate back to the planned waypoint path. Fig. 7 shows an
example of a rerouting map provided to participants during the Traveling + waypoint level 2 condition. The blue circle on this map denotes the planned waypoint to which participants were asked to reroute the robot. In purple is a hypothetical rerouting path a participant could have drawn. According to the scoring instructions listed in Table 3, the hypothetical path drawn in Fig. 7 would have been scored as a 4 on the measure of providing assistance to the robot.

Participants were instructed that rerouting the robot involved drawing the shortest path back to the planned path while simultaneously avoiding sensitive buildings in the environment (i.e., recreation centers and medical centers). Participants were instructed to avoid drawing a path that utilized roads that crossed in direct proximity to the sensitive buildings. Performance in rerouting the robot back to its planned path was scored on an additive scale where points were awarded for poor performance (e.g., routing the robot near sensitive buildings resulted in 3 points awarded; see Table 3.) As this was a reverse scored scale, lower scores derived using this scale were indicative of better assistance provided to the robot than higher scores. Perfect performance was indicated by a score of zero. Deviations from zero were indicative of increasingly worse performance in rerouting the robot.

Similar to the SA regarding the robot measure, providing assistance to the robot via rerouting the robot was assessed twice during each mission. For each mission, scores for both rerouting tasks were summed to provide an overall assessment of performance for each condition, and scores were summed across conditions to provide an overall assessment of performance for the study.

**Figure 7.** Hypothetical example of a rerouting path drawn in the Traveling + waypoint level 2 condition. The blue circle depicts planned waypoint number 3 in the robot’s planned path. The red X denotes the robot’s location at the time of the SA probe event. The route in purple denotes a possible path participants could have drawn to reroute the robot back to its planned waypoint path.
Table 3. Table of instructions for scoring each rerouting map drawn by participants to provide assistance to the robot.

<table>
<thead>
<tr>
<th>Scoring the rerouting maps as follows:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. If the route begins in the correct starting location</td>
<td>0 points</td>
</tr>
<tr>
<td>b. If the route does not begin in the correct starting location</td>
<td>20 points</td>
</tr>
<tr>
<td>2. Count the number of grid blocks that the drawn route crosses through</td>
<td># of blocks = # of points</td>
</tr>
<tr>
<td>3. Does the route utilize roads that cross in direct proximity to any sensitive buildings?</td>
<td>3 points for each sensitive building</td>
</tr>
<tr>
<td>4. Did the participant not draw a route when they should have done so?</td>
<td>20 points</td>
</tr>
<tr>
<td>5. Did the participant draw a route when should not have done so?</td>
<td>20 points</td>
</tr>
<tr>
<td>6. Sum these points together to obtain a rerouting score for each rerouting map.</td>
<td></td>
</tr>
</tbody>
</table>

Change detection performance. Participant performance on the change detection task was measured as the number change events correctly detected out of the total number of events present in each study condition.

Individual difference measures. Participants completed a biographical data form that contained questions pertaining to biographical information, such as, age, gender, prior military experience, and known color vision deficiencies. In addition, participants were asked a series of questions pertaining to their prior familiarity and experience with the robotics domain as well as robots intended for specific types of uses (e.g., robots for the home, robots for therapy/medical purposes, military robots). Participants rated their level of familiarity and experience (i.e., having worked with or come into contact with robots) on 6 point Likert-type scales that ranged from 1 (No experience, not familiar) to 6 (Very experienced, very familiar).

Participants also completed a computerized measure of visuospatial working memory via the Corsi block tapping task (Corsi, 1972), which involved watching a sequence of blocks presented on the computer screen light up with color in a random order. Participants were then asked to mimic the order in which the blocks lit up by clicking on each block with their mouse cursor in sequential order. As participants progressed through the task, the sequence of blocks became progressively longer and consequently more difficult to reproduce. Participants continued this procedure until performance began to degrade. Visuospatial working memory performance was measured as the number of blocks in the sequence that participants could reproduce.

Participants also completed the perspective taking/spatial orientation test (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). This test is a measure of individual ability to imagine different perspectives or orientations in space. For each item, participants were presented with a picture depicting an array of objects. For each item, participants were asked to imagine that they were standing at one object in the array, facing another object. Participants were then asked to draw an arrow in the direction of a third object from a different perspective. Participants were given 5 minutes to complete 12 items in this test. Each item in this measure was scored by the absolute deviation in degrees between the participants’ response and the correct direction to the target (absolute directional error). This measure was also reverse-scaled as more directional error was indicative of worse performance than less directional error. A participant’s total score on this measure is scored as the average directional error across all attempted items.
Procedure

Once in the lab, participants were presented with the informed consent form. Once the informed consent form was signed, participants completed the biographical data form along with the covariate measures, the perspective taking/spatial orientation test (Hegarty & Waller, 2004; Kozhevaknikov & Hegarty, 2001) and the Corsi block tapping task (Corsi, 1972). Once these measures were completed, participants moved into the training phase of the study.

The training phase of the study included viewing a narrated PowerPoint presentation with breaks included to provide opportunities to practice receiving updates from the robot, providing assistance to the robot, and answering SA regarding the robot questions. Once participants finished viewing the narrated PowerPoint presentation, they were asked to complete three practice missions in the MIX testbed. Practice missions were intended to represent shorter and simplified versions of the experimental missions completed in later phases of the study. All 3 practice missions were approximately 3 minutes and 30 seconds in length and included all elements of the experimental task. A separate and simpler overhead map of the team’s operating environment was developed for the training missions. Utilizing the separate map allowed participants to practice the elements of the experimental task while eliminating exposure to the overhead maps that would be used in the experimental phases of the study. The order of completion of the three practice missions was randomized within participants’ trials and counterbalanced across participants.

After the five-minute break, participants moved into the experimental phase of the study. During this phase, participants completed four experimental missions corresponding to each study condition. The order in which participants completed each scenario was counterbalanced utilizing a Latin squares design. While completing each scenario, participants were asked to answer SA regarding the robot questions and provide assistance to the robot via the rerouting drawing task when necessary. Once they were finished, participants were provided with post-participation information. The time to complete the entire study was approximately 2 hours and 30 minutes. Participants received course credit in return for their participation.

Results

This study was comprised of 56 male participants with ages ranging from 18 to 29 (M = 18.89, SD = 3.412). Participants were asked to report their knowledge and familiarity regarding robots and the robotics domain on a 6-point Likert-type scale. All participants reported low familiarity with robots (M = 2.44, SD = 1.162). Similarly, participants were asked to rate their experience (i.e., having worked with or come into contact with) robots on a 6-point Likert-type scale. All participants reported low experience with robots (M = 2.13, SD = 1.268). One participant reported prior active duty military experience, one participant reported that they had completed five weeks of basic training, and two participants indicated that they had four years of JROTC experience.

Hypotheses H1 and H2

A one-way repeated measures ANOVA with planned contrasts was conducted to test for significant differences in mean scores on the measure of SA regarding the robot across within-subjects study conditions. The test revealed a significant main effect for condition, Wilks Lambda = 0.636, F(3,53) = 10.131, p < .001, partial eta squared = .364.

Hypothesis H1 contrast. The contrast of mean scores on the measure of SA regarding the robot between the Waypoint status updates (A) condition (M = 8.82) and the Waypoint status updates (B) condition (M = 7.88) was not significant, p = .064. Further, mean scores trended in the opposite of the hypothesized direction. Hypothesis H1, which stated that more robot-to-human information exchanges would be associated with better SA regarding the robot than fewer robot-to-human information exchanges, was not supported.

Hypothesis H2 contrast. A contrast was also conducted to examine differences in mean scores on the measure of SA between the VPT conditions. A statistically significant difference was found between mean scores on the measure of SA between the Traveling + waypoint level 1 condition
\( (M = 7.64) \) and the Traveling + waypoint level 2 condition \( (M = 6.18) \), \( p = .002 \). However, mean scores trended in the opposite of the hypothesized direction. Hypothesis H2, which stated that robot-to-human information exchanges that include level 2 VPT context will be associated with higher levels of SA regarding the robot than robot-to-human information exchanges that include level 1 VPT context, was not supported.

**Additional contrast.** Finally, an additional contrast was conducted to examine the benefit of adding VPT information to robot-to-human information exchanges as opposed to simply adding more robot-to-human information exchanges on SA scores. Specifically, this was a contrast in mean scores on the measure of SA between the Waypoint status updates (B) condition \( (M = 7.88) \) and the Traveling + waypoint level 1 condition \( (M = 7.64) \). The difference between mean scores in the two conditions was not statistically significant, \( p = .637 \). Mean scores similarly trended in the opposite of the predicted direction. Table 4 and Fig. 8 present mean scores on the measure of SA across conditions.

Table 4. Table of means and standard errors for SA regarding the robot scores across study conditions.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Condition</th>
<th>Mean SA score</th>
<th>Std. Error</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission 1</td>
<td>Waypoint status updates (A)</td>
<td>8.82</td>
<td>.36</td>
<td>56</td>
</tr>
<tr>
<td>Mission 2</td>
<td>Waypoint status updates (B)</td>
<td>7.88</td>
<td>.37</td>
<td>56</td>
</tr>
<tr>
<td>Mission 3</td>
<td>Traveling + waypoint level 1</td>
<td>7.64</td>
<td>.38</td>
<td>56</td>
</tr>
<tr>
<td>Mission 4</td>
<td>Traveling + waypoint level 2</td>
<td>6.18</td>
<td>.36</td>
<td>56</td>
</tr>
</tbody>
</table>

![Scores on measure of SA regarding the robot](image_url)

**Figure 8.** Pattern of mean scores on the measure of SA regarding the robot and planned contrasts across within-subjects study conditions.
Hypotheses H3

Hierarchical multiple regression was used to assess the relationship between scores on the measure of SA regarding the robot and scores on the measure of assistance provided to the robot while controlling for individual difference covariates. For this test, aggregate scores of SA regarding the robot and assistance provided to the robot across all four study conditions were used. Scores on the measure of providing assistance to the robot were reversed before conducting the analysis to aid in the interpretation of the results, so that higher SA scores would be predictive of higher assistance scores.

Scores on the measures of visuospatial working memory (Corsi block tapping task), spatial orientation (perspective taking/spatial orientation test), and prior robotics experience were entered at Step 1 and explained 10% of the variance in scores on the measure of providing assistance to the robot, $R^2 = .100$, $F(4, 51) = 1.422$, $p = .240$. After scores on the measure of SA regarding the robot were entered at Step 2, the overall model explained 33.9% of the variance in scores on the measure of assistance provided to the robot, $R^2 = .339$, $F(5, 50) = 5.132$, $p = .001$, representing a significant change in the amount of variance explained by the model, $R^2$ change = .239, $p < .001$. After controlling for the scores on the measures of individual differences, the only variable to make a significant unique contribution to explaining variance in scores on the measure of providing assistance to the robot was scores on the measure of SA regarding the robot, $beta = 1.738$, $p < .001$. Hypothesis H3, which stated that higher SA regarding the robot will be positively associated with superior human assistance provided to the robot, was supported.

Additional analysis: Analysis by level of SA

Additional analyses were conducted to investigate the effects of the experimental conditions on participants’ ability to attain the different levels of SA (level 1 perception, level 2 comprehension, and level 3 projection). Participant scores on the measure of level 1 SA were calculated by summing their correct responses to the level 1 SA questions across the four study conditions. The same procedure was repeated for the level 2 and level 3 SA questions. Three one-way repeated measures ANOVAs were conducted to test for significant differences in mean scores on the measures of level 1, level 2, and level 3 SA across study conditions. The tests revealed significant main effects for condition on level 1 SA scores, Wilks Lambda = 0.499, $F(3, 53) = 17.762$, $p < .001$, partial eta squared = .501, and level 2 SA scores Wilks Lambda = 0.197, $F(3, 53) = 71.966$, $p < .001$, partial eta squared = .803. A significant main effect for study condition on level 3 SA scores was not found Wilks Lambda = 0.873, $F(3, 53) = 2.581$, $p = .063$, partial eta squared = .127. (See Table 5 and Fig. 9.)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Condition</th>
<th>Level 1 SA score (Mean (std. error))</th>
<th>Level 2 SA score (Mean (std. error))</th>
<th>Level 3 SA score (Mean (std. error))</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Waypoint status updates (A)</td>
<td>1.63** (0.08)</td>
<td>3.61*** (0.14)</td>
<td>3.59** (0.25)</td>
<td>56</td>
</tr>
<tr>
<td>2</td>
<td>Waypoint status updates (B)</td>
<td>1.50*** (0.07)</td>
<td>2.68*** (0.18)</td>
<td>3.70 (0.24)</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>Traveling + waypoint Level 1</td>
<td>1.79* (0.10)</td>
<td>1.86* (0.19)</td>
<td>4.13 (0.27)</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>Traveling + waypoint Level 2</td>
<td>1.00 (0.10)</td>
<td>0.79 (0.15)</td>
<td>4.39 (0.25)</td>
<td>56</td>
</tr>
</tbody>
</table>

Note: a = contrast between 1 & 2, b = contrast between 1 & 3, c = contrast between 1 & 4, d = contrast between 2 & 3, e = contrasts between 2 & 4, f = contrast between 3 & 4. *contrast significant at $p < .05$, **contrast significant at $p < .001$. 

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Additional analysis: Change detection task

Additional analyses were conducted to examine the effects of robot-to-human information exchanges and level of VPT information on participant performance on the change detection task. The future vision of soldier-robot teams is one in which the robot and the soldier complete separate but interdependent tasks. If the robot’s information exchanges hinder the soldier’s ability to perform his/her individual activities then the practical utility of robot-to-human information exchanges will be diminished. Thus, additional analyses were conducted to better understand the impact of information exchanges on dual-task performance.

A one-way repeated measures ANOVA with scores on the measure of change detection performance as the within-subjects variable was used to test for significant differences in dual-task performance across within-subjects conditions. There was a significant effect across study conditions, Wilks Lambda = 0.470, $F(3,51) = 19.202, p < .001$, partial eta squared = .530. (See Table 6 and Fig. 10 for mean scores on the change detection task across study conditions.)

Post-hoc comparisons showed that there were significant differences in scores on the change detection task between the Waypoint status updates (A) condition ($M = 38.93$) and the Waypoint status updates (B) condition ($M = 30.46$), $p < .001$. There also were significant differences

Table 6. Table of means and standard errors on the change detection task across study conditions.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Condition</th>
<th>Mean CD Scores</th>
<th>Std. Error</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission 1</td>
<td>Waypoint status updates (A)</td>
<td>38.93</td>
<td>1.01</td>
<td>54</td>
</tr>
<tr>
<td>Mission 2</td>
<td>Waypoint status updates (B)</td>
<td>30.46</td>
<td>1.15</td>
<td>54</td>
</tr>
<tr>
<td>Mission 3</td>
<td>Traveling + waypoint Level 1</td>
<td>33.09</td>
<td>1.23</td>
<td>54</td>
</tr>
<tr>
<td>Mission 4</td>
<td>Traveling + waypoint Level 2</td>
<td>34.09</td>
<td>1.06</td>
<td>54</td>
</tr>
</tbody>
</table>
between change detection scores in the Waypoint status updates (B) condition ($M = 30.46$) and the Traveling + waypoint status updates level 1 condition ($M = 33.09$), $p = .008$. Significant differences were not found between scores on the change detection task between the level 1 ($M = 33.09$) and level 2 conditions ($M = 34.09$), $p = .260$.

![Change detection task scores](image)

*Figure 10.* Pattern of mean scores and contrasts between change detection task scores. Scores represent the mean number of change detection events correctly detected by participants.

**Additional analysis: Order of completion of conditions**

Additional analyses were conducted to determine if the order in which participants completed each mission may have helped to explain the pattern of mean SA scores that trended in the opposite of the hypothesized direction. A one-way between-subjects ANOVA, with the order in which participants completed the study conditions as the between-subjects variable and SA regarding the robot scores as the dependent variable, was conducted to test for significant differences in scores on the measure of SA due to the order in which participants completed each study condition. The ANOVA test revealed that there were no significant differences in SA scores due to the order of completion of the study conditions, $F(7, 48) = 1.042$, $p = .415$. Although there were no significant effects associated with the order in which participants completed the study conditions, the pattern of means revealed that there may have been a practice benefit to interpreting the level 2 VPT information. If participants completed the level 2 condition as the last mission (i.e., the 4th trial), their SA scores for that mission were higher than if they completed the level 2 condition in any other trial during the course of the study. Conversely, if participants completed the level 2 condition in the first trial, SA scores for that condition were lower than if they completed the condition in any other trial during the course of the study. Participants had the highest SA scores if the level 2 condition was completed last and the lowest SA scores if the level 2 condition was completed first. (See Table 7 for mean SA scores for each condition as a function of when that condition was completed in the study.)
Table 7. Table of mean SA scores for each condition as a function of which trial the condition was completed.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean SA scores for each condition by Trial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
</tr>
<tr>
<td>Waypoint status updates (A)</td>
<td>9.79</td>
</tr>
<tr>
<td>Waypoint status updates (B)</td>
<td>8.08</td>
</tr>
<tr>
<td>Traveling + waypoint Level 1</td>
<td>9.21</td>
</tr>
<tr>
<td>Traveling + waypoint Level 2</td>
<td>5.53</td>
</tr>
</tbody>
</table>

Discussion

Hypotheses H1 and H2

Hypotheses H1 and H2 posited that more robot-to-human information exchanges and higher levels of VPT information would be associated with higher levels of SA than fewer robot-to-human information exchanges and lower levels of VPT information. Neither of these hypotheses was supported, as the pattern of mean scores on the measure of SA trended in the opposite of the hypothesized directions.

The finding for Hypothesis H1 may be due to increasing demands placed upon the human by receiving updates from the robot too often for this study design. Each of the four experimental missions was scripted to last approximately 5 minutes in duration. In the Waypoint status updates (A) condition, participants received robot-to-human information exchanges in the form of status updates 7 times, with approximately one update every 45 seconds, beginning after the 30 second mark. The Waypoint status updates (B) condition was also 5 minutes in duration, but participants received waypoint status updates 13 times, with approximately one update every 22–24 seconds, beginning after the 30-second mark. Thus, when the number of updates in each mission was increased, the interval between updates was reduced in half. It is possible that participants were having trouble attending to the information provided to them by the robot, or dealing with the frequency of the waypoint updates, as well as maintaining performance on the other tasks. This is supported by evidence from participant performance on the change detection task. Specifically, the increase in the number of updates sent by the robot between the Waypoint status updates (A) and the Waypoint status updates (B) conditions not only decreased scores on the measure of SA regarding the robot but also dual-task performance on the change detection task by an amount that was statistically significant.

Building SA regarding the robot required participants to use the information contained in the information exchanges to locate the robot’s position on the overhead map of the environment. Doubling the number of waypoint updates required participants, at the very least, to attend to the overhead map twice as many times, which would have required participants to take eyes off the screen that displayed the robot-to-human information exchanges in twice as many instances. Thus, simply having “eyes off” the robot-to-human information exchanges and the change detection task could also help to explain drops in both SA and in change detection performance.

However, while the requirement to take “eyes off” was not ideal for maintaining high levels of performance in this study, it does simulate some of the elements of what soldiers will be required to do when teaming with robots in field environments in the near future. Meaning that, when robots are fielded alongside soldiers, soldiers will likely need to periodically divert attention away from their immediate task(s) and dedicate attention to the robot. It seems, however, that the frequency or number of updates simulated in the Waypoint status updates (B) condition may have increased demands by much that individuals had a difficult time attending to the robot while maintaining performance on other tasks, which is not ideal.

Hypothesis H2 stated that higher levels of VPT information added to robot-to-human information exchanges would be associated with higher levels of SA than lower levels of VPT information. This hypothesis was not supported. The pattern of mean scores on the SA measure
revealed that higher levels of VPT context added to robot-to-human information exchanges resulted in statistically significant lower scores than lower levels of VPT context.

There are a few reasons that might help to explain this finding. The first is related to the potential benefit of practice in completing the experimental tasks. It seemed that participants may have needed more practice to do well interpreting the clock face spatial reference frames provided in the level 2 VPT condition. In fact, if participants completed the level 2 condition (i.e., the clock face reference frame condition) as the last mission (i.e., the 4th trial), their SA scores for that mission were higher than if they completed the level 2 condition in any other trial during the course of the study. Conversely, if participants completed the level 2 condition in the first trial, SA scores for that condition were lower than if they completed the condition in any other trial during the course of the study. Participants had the highest SA scores if the level 2 condition was completed last, and they had the lowest SA scores if the level 2 condition was completed first. It is possible that practice helped participants to develop automaticity for some elements of the experimental tasks or aided participants in developing better strategies for completing tasks, which may have helped them free up any additional resources that were needed to fully understand or make use of the clock face reference frames for developing SA.

There is some evidence to suggest (although not conclusively) that adolescents and young adults are less familiar with analog timekeeping (the operationalization of level 2 VPT for this study) than older adults (Fendrich, 2008, Freeman; 2009; Merz, 2014; Webb, 2014). Due to the young average age of the participants in this study and lack of prior military experience for most participants, it is possible that the likelihood of participants being less versed in analog timekeeping was high. This could have made using reference frames that rely on familiarity with analog timekeeping more difficult or less intuitive, as opposed to more intuitive, as originally hypothesized. The findings from the additional analyses investigating the effect of the study conditions on the development of level 1 and level 2 SA support this interpretation as well. Level 1 and level 2 SA scores were the lowest in the level 2 VPT condition. Level 2 VPT information did seem helpful in supporting level 3 SA (projection). However, it is difficult to know how helpful this information is in supporting spatial understanding of the environment. More of the level 3 SA questions concerned making projections about if the robot would complete its route. Fewer level 3 SA questions concerned making projections about the direction the robot would need to travel.

It is also possible that the use of clock face directions may not have been a strong enough operationalization of the level 2 VPT construct to be beneficial. A look at some of the literature on perspective-taking communications used in human-human teams suggests that when people communicate level 2 information in another’s point of view, they spend a large amount of their overall utterances doing so (Shelton & McNamara, 2004). Also, many utterances are spent trying to ground information before spatial information is communicated (Trafton et al., 2005). In the current study, a stronger (or perhaps different) operationalization of level 2 context added to robot-to-human information exchanges may have been needed to better support the level 2 construct and VPT theory.

The addition of level 1 VPT information seemed easier to process and may have helped to mitigate some of the performance decrements associated with hearing from the robot too often. In both the Waypoint status updates (B) condition and the Traveling + waypoints level 1 conditions, participants received the same number of robot-to-human information exchanges and both had roughly equivalent aggregate SA scores. The addition of the level 1 VPT information was most helpful for perceiving the relevant features of the task environment. The level 1 VPT condition had the highest level 1 SA scores. The addition of the level 1 information significantly improved participants’ change detection scores as well. Overall, these findings suggest that the level 1 VPT information may have been easier to interpret and less likely to detract from participants’ dual-task performance than level 2 VPT information.

Hypothesis H3

Hypothesis H3 stated that higher levels of SA would be positively associated with superior human assistance provided to the robot. The result of the test of Hypothesis H3 demonstrated that SA regarding the robot is a strong predictor of providing better assistance to the robot when the robot
is having trouble executing tasks as planned. This finding supports the idea that if robots can be designed in ways that promote a human’s awareness of when interventions in robot tasks are needed, humans will be better able to provide those interventions and ultimately ensure the success of the team. When participant SA regarding the robot was high, participants were much better at providing assistance to the robot than when participant SA was low. On average, participants with high SA scores performed 25% better on the measure of assistance provided to the robot than participants with low SA scores. These are important findings as they suggest that at a minimum, robots that work in teams with humans should support their human partners’ awareness regarding progress and status. Humans can use that awareness to make appropriate interventions in robot tasks when needed.

Conclusions

These findings have practical implications for fielding robots that do not yet perfectly replicate human capabilities. Specifically, human-level capabilities or full-human emulation may not be a necessary precondition to support teams of humans and robots completing tasks together. It is very likely that robots in the near term will not possess the metacognitive capabilities necessary to know when they are performing poorly or when to ask for human help. However, these results have helped to illustrate that if robots in the near term can provide status information that assists humans in knowing when robots are not performing well, then humans will be better prepared to provide the assistance that robots need and ultimately help the team to continue their mission.

Although the majority of the results of the study did not turn out as originally hypothesized, the results provide some insight into potential best practices for facilitating situation awareness regarding the robot and assistance provided to the robot. In terms of practical utility, it is promising to note that relatively few information exchanges from the robot were needed to support the highest levels of SA in this study overall. With size, weight, and computing restrictions, designers of robotic teammates intended to be deployed in the near term will be contending with practical tradeoffs concerning the inclusion of various hardware used to support robot sensing and information processing onboard the machine itself. Therefore, it is practically important to note that our participants were able to determine from relatively few information exchanges and less contextual information the location of the robot, as well as implications associated with its surroundings. These findings could mean that designers may be able to devote less sensing hardware and computing resources to robot-to-human information exchanges than originally hypothesized, the result of which may translate into space and cost savings overall.

It also should be noted that there may be a point at which hearing from the robot too often becomes detrimental for the human teammate to carry out their own individual tasks. In this study, hearing from the robot roughly 3–4 times a minute seemed to be detrimental, whereas roughly 1–1.5 times a minute was more manageable. This is important, because recent research studies in which participants were asked to request robot status reports when they felt necessary found that participants requested reports at a frequency closer to the 3-5 times per minute as opposed to 1–2 times per minute—the frequency which resulted in the highest levels of SA in this study (Abich et al., 2016). Thus, if status updates from the robot are needed or desired by users at a greater frequency, it may be best to include periodic traveling status updates that present information with reference to global-relative directions when possible.

Finally, the condition with the fewest information exchanges had the highest SA scores, change detection scores, and adequate scores on the measure of providing assistance to the robot. These findings are somewhat consistent with studies conducted with human-human teams operating under shifting workload conditions. Researchers have described that when members of high-performing, human-human teams shift from low workload conditions to operating under high workload conditions, they often exhibit patterns of communication marked by a reduction in information sharing, resulting in more efficient team communication overall (MacMillan, Entin, & Serfaty, 2004; Urban, Bowers, Monday, & Morgan, 1993). For fielding future human-robot teams, if the robot can sense that the human is having trouble dual tasking, the robot may be able to adjust the frequency with which it sends updates, and thus support the ability of the human to complete all mission tasks.
Limitations and future research

There are several limitations to this study that are important to note. The first is that the participant sample used was limited in age (age range 18–29) as well as gender (all males) and both military and robotics-relevant experience. Recommendations generated from this study may not generalize well to the military population at large.

Further, the modality in which information was shared with the human by the robot was not a variable that was manipulated in this study. The robot-to-human information exchanges were always presented to participants through text exchanges. A primary purpose of the study was to test whether the addition of VPT information was helpful in building and maintaining SA, not whether the text modality is necessarily the best way to present robot-to-human information exchanges. It is possible that presenting robot status information through different, multiple, or redundant modalities (e.g., speech, text, tactile, or some combination of) will show a different pattern of results. For instance, using the auditory modality in combination with the visual modality could reduce the burden of dual tasking on the visual processing system by making use of multiple information processing channels (Wickens, 2002) and addressing potential problems with needing to take “eyes off” the change detection task. Further, multiple or redundant modalities in addition to audio and text may be needed to overcome practical challenges present in battlefield environments (e.g., the need to communicate with stealth or the need to communicate in very loud battlefield environments). Both basic and applied research is needed to investigate whether SA regarding the robot can be improved if information exchanges from the robot are presented in modalities other than text alone, whether those modalities can be robust in various operational environments, and whether interacting with a real robotic platform would show a different pattern of results.

It is also worth noting that SA measurement is notoriously difficult and is a topic of much disagreement among research scientists (Pritchett, 2015). The SA measurement technique for this study may not have accurately captured all of the relevant information needed to do well in the study or in real-world environments.

Finally, this study only assessed whether robot-to-human information exchanges could support three different levels of awareness information, those conceptualized according to Endsley’s SA (1995a) model. However, research by Drury, Keyes, and Yanco (2004) described that there are five different types of awareness relevant for good HRI performance in ecologically valid scenarios with real robots (e.g., location awareness, activity awareness, surroundings awareness, status awareness, and overall mission awareness). This study did not look at the effect of information exchanges on awareness about obstacles in the robot’s environment or the robot’s status, such as power supply or other health-related information. Thus, it would be pertinent to investigate the role of information exchanges and levels of VPT on different types of awareness regarding the robot and not just different levels as conceptualized under the Endsley model of SA.

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