Bodies in Motion: Mobility, Presence, and Task Awareness in Telepresence

Irene Rae
University of Wisconsin–Madison
1210 West Dayton Street
Madison, WI 53706, USA
irene@cs.wisc.edu

Bilge Mutlu
University of Wisconsin–Madison
1210 West Dayton Street
Madison, WI 53706, USA
bilge@cs.wisc.edu

Leila Takayama*
Willow Garage, Inc.
68 Willow Road
Menlo Park, CA 94025, USA
takayama@willowgarage.com

ABSTRACT

Robotic telepresence systems—videoconferencing systems that allow a remote user to drive around in another location—provide an alternative to video-mediated communications as a way of interacting over distances. These systems, which are seeing increasing use in business and medical settings, are unique in their ability to grant the remote user the ability to maneuver in a distant location. While this mobility promises increased feelings of "being there" for remote users and thus greater support for task collaboration, whether these promises are borne out, providing benefits in task performance, is unknown. To better understand the role that mobility plays in shaping the remote user's sense of presence and its potential benefits, we conducted a two-by-two (system mobility: stationary vs. mobile; task demands for mobility: low vs. high) controlled laboratory experiment. We asked participants (N = 40) to collaborate in a construction task with a confederate via a robotic telepresence system. Our results showed that mobility significantly increased the remote user's feelings of presence, particularly in tasks with high mobility requirements, but decreased task performance. Our findings highlight the positive effects of mobility on feelings of "being there," while illustrating the need to design support for effective use of mobility in high-mobility tasks.

Author Keywords

Remote collaboration; robotic telepresence; robot-mediated communication; mobility; presence; task awareness

ACM Classification Keywords

H.4.3 Information Systems Applications: Communications Applications—*computer conferencing, teleconferencing, and videoconferencing*

INTRODUCTION

Videoconferencing systems have seen use as early as the 1970s [43]. Since that time, researchers, inventors, and designers have sought to bring video-mediated communications closer to face-to-face interactions, to simulate the sensation of actually "being there." A common approach to achieving this goal has been to improve audio [38] and visual connections [9] between remote communication partners. Another approach has been to augment videoconferencing systems with robotic platforms, also known as robotic telepresence systems [16, 29]. By enhancing the sensation of "being there" in the remote location, or *presence*, these systems promise to impart some of the same benefits that being physically present would provide, such as increased coordination and awareness. Through capabilities such system maneuverability, laser pointers as

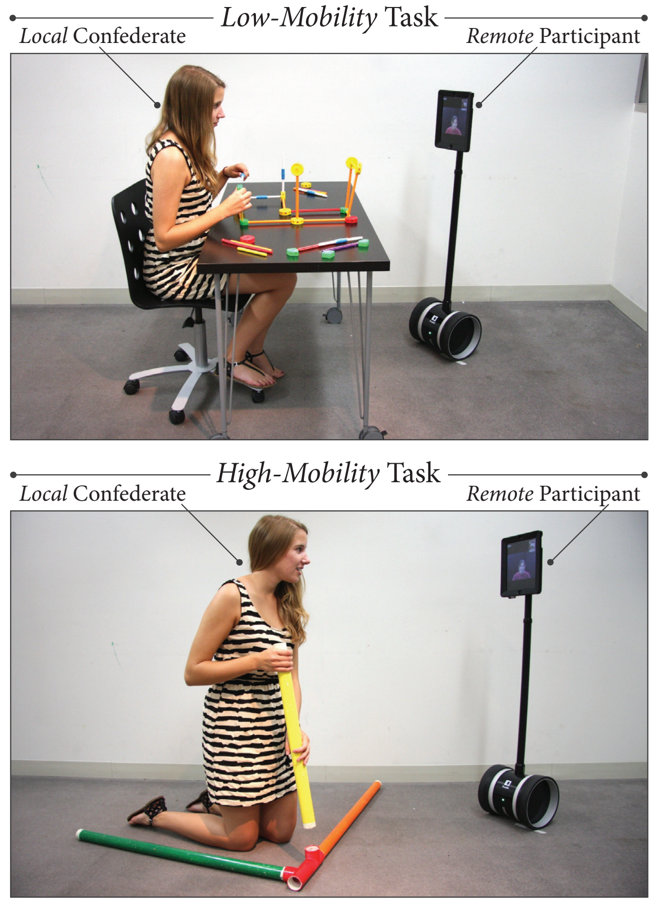

Figure 1. Participants remotely collaborated with a local confederate in a construction task that either took up a small amount of desk space, requiring *low* levels of mobility, or a large amount of space, requiring *high* levels of mobility, in the room.

*Author now at Google[x], takayama@google.com

CHI 2014, April 26–May 1, 2014, Toronto, Ontario, Canada.

ACM 978-1-4503-2473-1/14/04..$15.00.
http://dx.doi.org/10.1145/2556288.2557047

deictic indicators, and the provision of a physical embodiment, research on robotic telepresence systems has explored ways to support increased presence for remote users. For example, past studies have demonstrated that robotic telepresence systems increased the local users' feelings of the remote user's presence, improving collaborative team outcomes [23, 31, 41]. However, few studies have examined the effects that these systems may have on the remote user's, the *remote's*, perceptions of their own presence in the local environment.

In domains such as manufacturing, construction, or exploration, the ability to change perspectives and maneuver in the environment may not only enable the remote user to offer the local user guidance and instruction, but may also directly contribute to task completion. By enabling the remote user to interact with the surrounding space, these systems may increase the remote's awareness of the physical environment, facilitating task-oriented actions, such as mapping an area, locating objects, and conducting visual checks. However, because many of these systems have been designed for use in office settings [2, 11, 17, 33, 34, 42], previous literature has primarily focused on the contexts of conversation and collaborative meetings. In these scenarios, once the system has been positioned in front of the local user, the *local*, the mobility of the system no longer plays a key role, and the robotic platform becomes the equivalent of a videoconferencing display. As a result, how mobility affects the remote's sense of presence and contribution to task outcomes, particularly in settings where maneuverability directly impacts task completion, is unclear.

Our goal in this study is to investigate the role that mobility plays in instilling a sense of presence in the remote user and to increase our understanding of how it may improve team performance in physically oriented tasks. Specifically, we seek to gain a better understanding of how mobility supports the remote user's contributions in tasks that require different levels of mobility (Figure 1)—in tasks that are visible from a single view, requiring *low* levels of mobility, and tasks where the ability to maneuver gives the remote user greater latitude to participate in the completion of team goals, i.e., tasks with *high* requirements for mobility. By exploring these questions, we hope to inform the future design of mobility features for robotic telepresence systems and to deepen our understanding of how mobility shapes remote collaboration.

The next section provides an overview of related work on remote collaboration, focusing specifically on presence and task awareness. This overview is followed by a description of our hypotheses and our study design. We then present our results and discuss their implications for design and research. Finally, we summarize the study's limitations, areas for future work, and our conclusions.

RELATED WORK

Previous work on supporting remotely distributed teams has focused on the importance of *workspace awareness*—how knowledge and awareness of where others are working and what they are doing might facilitate the coordination of action [20]—and on supporting *grounding*—the process of creating common ground to achieve mutual understanding [5]. For both workspace awareness and grounding, the ability to track the presence and spatial positioning of others is key for successful collaboration. In this section, we provide an overview of work that has examined presence and task awareness in both virtual and physical telepresence environments.

Presence

The domain of workspace awareness in computer-supported cooperative work focuses on improving collaborative outcomes by simulating a physical workspace in a virtual environment. By designing tools that provide users with timely information about the task at hand, such as who is present, where they are working, and what they are doing, these systems translate the affordances found in physically shared workspaces into online tools that support group work [8, 14, 18, 20]. For example, by using digital representations of user arms to create a sense of where they are active in a virtual workspace [12], providing historical logs of past exchanges [13], and preserving spatial relationships [36], these systems facilitate coordination between users and improve group efficiency. In these examples, indicators of collaborator presence are implemented as representations of information, such as positioning and availability, that users would have access to in a non-virtual workspace.

Previous research on robotic telepresence has examined how having a physical embodiment might support the remote user's presence in the local user's environment. Findings from this work have demonstrated that these platforms improve the local users' sense of the remote user's presence, increasing the frequency of informal interactions between co-workers—shown to be critical for organizational coordination [22]—and the remote user's ability to participate in meetings [23, 41]. Additional research has examined how other aspects of robotic telepresence systems shape interactions, such as the effects that embodiment and control have on the development of trust between users in negotiation tasks [31], how the height of the system shapes the local's perceptions of the remote user's persuasiveness [32], and the role that system appearance plays on the local's feelings of team membership toward the remote user [30]. Previous work has also explored manipulating the camera's mobility in a telepresence system to increase the remote user's feelings of presence; however, the stationary nature of the task and the camera's limitations resulted in few users utilizing this capability, making it difficult to draw definitive conclusions [28].

While this past research illustrates how various aspects of robotic telepresence systems affect and improve the local user's perceptions of the remote user's presence [1], we lack a clear understanding of whether these systems truly improve the remote user's sense of "being there" in the local environment.

Task Awareness

Research in workspace awareness has explored different ways of conveying critical information and supporting grounding by informing users about movement within the online workspace. For example, prior work has explored the use of workspace miniatures to show the location and activity of others in the workspace [19] and the use of indicators of availability [8] to aid in collaborative coordination.

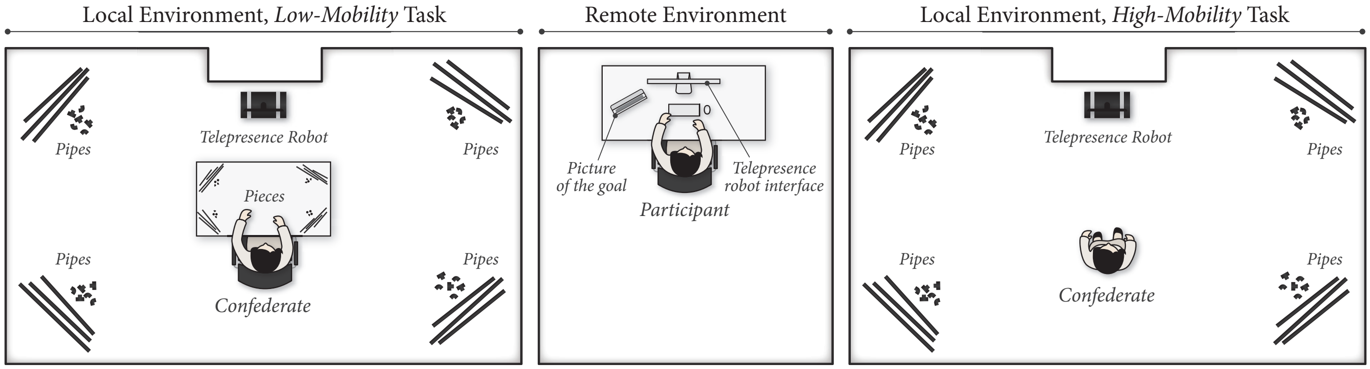

Figure 2. The physical arrangements of the study room in the *low-mobility* task condition, the participant's environment, and the study room in the *high-mobility* task condition on the left, center, and right, respectively.

Within the sphere of robotic telepresence, prior literature has sought to understand user needs for movement and awareness within specific contexts, such as office [23, 40], medical [6, 39] and educational [15] settings. Research in teleoperation has explored the design of control interfaces that aid remote users in being aware of their surroundings to accomplish solo exploration tasks, including the avoidance of obstacles and successful navigation [16, 24, 26]. While these bodies of work inform the design of interfaces that more effectively support mobility in the remote environment, they do little to aid us in understanding how such mobility facilitates task awareness, coordination, and feelings of presence. Mobile telepresence systems offer a unique opportunity for remote users to not only benefit from the tools developed in workspace awareness research and teleoperation, but also to directly contribute to tasks in a physical workspace.

In our study, we seek to understand the contribution that mobility may have in supporting remote users' feelings of presence, facilitating their ability to contribute to task completion. To this end, we focus on two types of tasks: tasks where mobility requirements are low and movement does not aid in the completion of goals, such as conversations, negotiations, and activities limited to a small workspace, and tasks where the requirements are high and the ability to move in the physical space facilitates performance, such as construction, manufacturing, and exploration. In other words, when does mobility matter?

HYPOTHESES

Informed by previous research in workspace awareness and robotic telepresence systems, we formed two hypotheses predicting the role that the mobility of the system would play in different task types.

Hypothesis 1. Remote users will report more presence in the local's environment when the system is mobile than when the system is stationary.

Hypothesis 2. In a task that requires high levels of mobility, using a mobile system will improve collaborative outcomes over using a stationary system, while mobility of the system will not affect these outcomes in a task that requires low levels of mobility.

METHOD

To test these hypotheses, we designed a controlled laboratory experiment in which remote participants worked with a local confederate in a collaborative construction task. In the study, we manipulated the mobility of the robotic telepresence system and the movement or mobility required by the task. We measured the effects of these manipulations on the participant's sense of presence in the local environment and team task performance outcomes, such as completion time and errors. The paragraphs below provide further detail on our study design, participants, measurements, and analyses.

Study Design

Our study followed a two-by-two between-participants design. The independent variables were *mobility*, varied by the use of a stationary or mobile robotic telepresence system, and the levels of *mobility or movement* required by the task, low vs. high. In order to maintain consistency across participants, we developed a task to construct an object that could be built on a small scale with TinkerToys, or on a large scale with PVC pipes. When built on a small scale, the completed object measured approximately 22 inches (55.88 cm) in length and 3.5 inches (8.89 cm) in height, fitting on a table that was fully visible from the telepresence system's camera. When constructed on a large scale, the completed object measured approximately 7 feet (182.88 cm) in length and 3 feet (91.44 cm) in height, requiring it to be built in a clear floor space that was not easily visible from the telepresence system's camera. The construction of small-scale and large-scale objects served as *low-mobility* and *high-mobility* tasks, respectively. Figure 2 illustrates the arrangement of the study environment across the task manipulation.

Although both local and remote users of a telepresence robot may benefit from the level of mobility that the remote user has, we were chiefly interested in the remote user's experience and perspective for two reasons. First, prior work has primarily been dedicated to understanding robotic telepresence interactions from the local user's perspective [30, 32, 1]. Second, because face-to-face interaction participants have the ability to move in the environment, we expected that providing the remote user with the ability to maneuver would have a greater impact on the remote user's experience. To this end, we asked participants to act as the remote user and used a

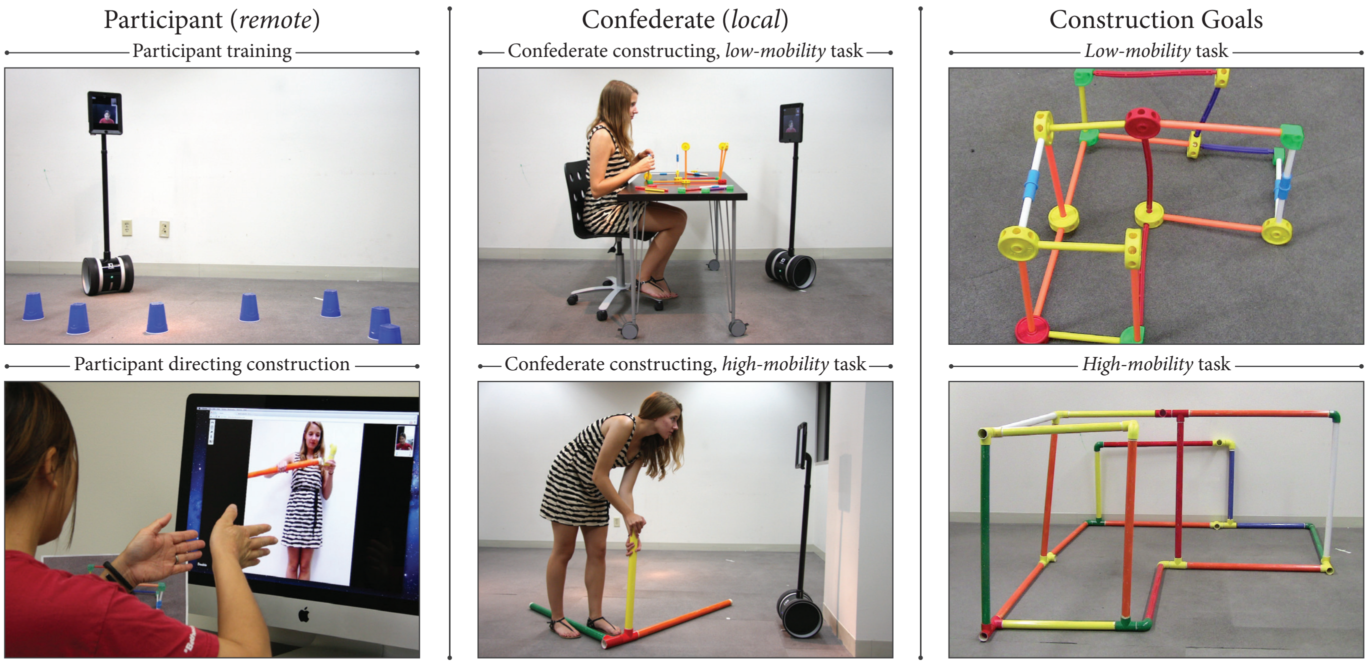

Figure 3. *Left*: participant controlling the telepresence robot in the training phase and the remote setup in which they provided the confederate with instructions. *Center*: the local setup for the low mobility and high mobility task conditions in which the confederate carried out the construction of the object. *Right*: pictures of the completed objects for the small and large tasks provided to the participant.

confederate—one of our experimenters, who pretended to be a participant—as the local user in our task. The locations of the participant and the confederate are illustrated in Figure 2.

System

Both stationary and mobile interactions in our study took place via a Double telepresence robot[1] (shown in Figure 1), which has a weight of 15 pounds and an height that is adjustable to either 47 inches or 60 inches (101.6cm to 152.4cm). The Double allows remote users to drive in the local's environment, switch between a front and bottom-view camera, and adjust the height to two different settings. The telepresence robot's screen was an Apple iPad 2 tablet computer[2] with a diagonal screen size of 9.7 inches (24.64 cm) and a screen resolution of 2048×1536 and 264 ppi. The front camera of the tablet computer provided a video stream of what the system was facing to aid with communication, and the back camera showed the immediate surroundings of the robot using a mirror directed toward the ground to aid with navigation.

The participant and the confederate communicated via the Double videoconferencing interface, shown in Figure 3. In the stationary condition, participants were not instructed on the controls for moving the system and the system was plugged into the wall, preventing movement. In the mobile condition, participants were provided with an instruction sheet on the controls for moving the system and were able to freely maneuver around in the experiment room.

Construction Task

In our study, participants engaged in a construction task with a confederate where the pieces were either small, 3.35 inches (8.51cm) to 10.85 inches (27.56cm) in length, or large, 2 feet (60.96cm) to 3 feet (91.44cm) in length. The completed object had a total of 35 parts—22 straight pieces and 13 connecting joints—with varying orientations and colors. Participants were told that they would be working together with another study participant to build the object, that they would have the instructions, and that the other person would have the parts. We motivated participants to work as quickly and accurately as possible by adding an incentive; if they were able to build the correct object faster than any other teams from the study, they would receive an extra dollar. They were also told that they could begin the task as soon as the timer was started and that the timer would stop when they told the experimenter that they were finished. Participants received a picture of the completed object that they were not allowed to show to the confederate, as shown on the right in Figure 3.

Measures

To measure the collaborative outcomes of the construction task, we utilized a number of objective and subjective measures.

Measures of Presence

In order to measure the remote user's feelings of presence, we asked participants to mark where they and their partner worked during the task on a map of the rooms. Figure 4 shows example data from this measure. Markings on the map were coded as "in-room" if participants noted that they and the confederate were in the room where the object was being constructed. They were coded as "separate" if participants marked that they and the confederate operated from separate rooms. In order to avoid biasing participants, the map of the room was not changed between conditions, but participants were warned that the layout of the rooms or the objects included on the map may not be accurate.

[1]http://www.doublerobotics.com/
[2]http://www.apple.com/ipad/

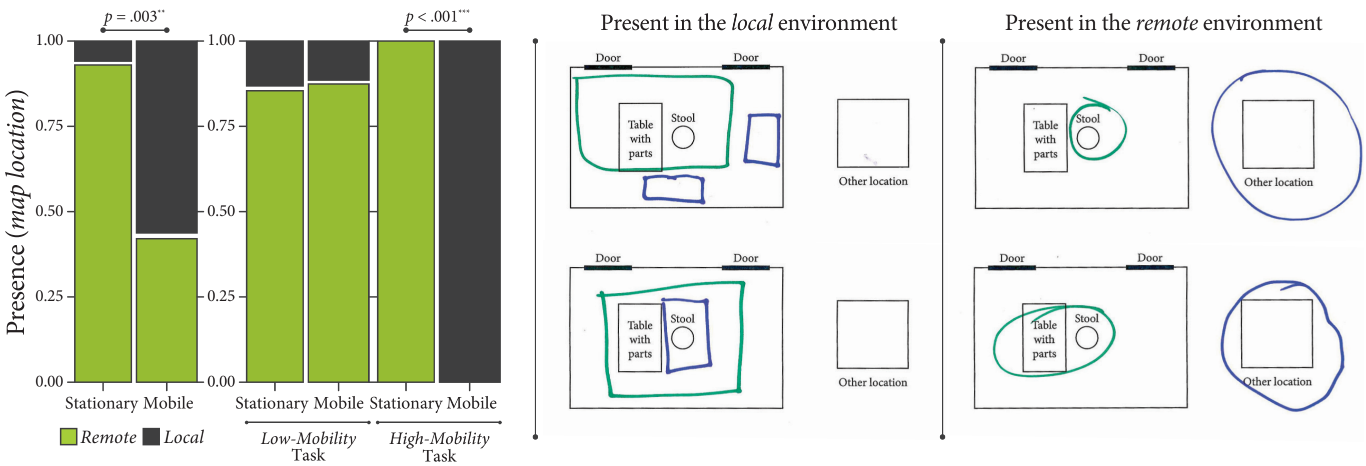

Figure 4. *Left*: Data from the measures of presence across mobile and stationary conditions and broken down to tasks requiring low and high levels of mobility. (***) and (**) denote $p < .001$ and $p < .01$, respectively. *Center and right*: Example data from the presence measure, participants used blue to circle the area that they worked in and green to circle the area that their partner worked in. The examples in the center illustrate data from participants who felt present in the room where they were tele-present, rather than the "other location" where they were physically located, and those on the right illustrate data from participants who felt present where they were physically located.

Measures of Task Performance

We used the time taken to complete the construction of the object as a measure of task efficiency. Time was marked in seconds from when the timer was started to when the participant opened the door of the study room and announced that they were finished. The number of mistakes in the completed object, i.e., errors in the orientation or position of the pieces, served as a measure of task accuracy.

Other Measures

While we did not pose any specific hypotheses about subjective evaluations, we created an exploratory post-experiment questionnaire to better understand the effects that the mobility of the system might have on the remote user's perceptions of teamwork, team recovery, workspace awareness, and environmental awareness. Participants were asked to rate their agreement on a five-point Likert scale, 1 = Strongly disagree, 5 = Strongly agree, with 34 statements (e.g., "I was aware of my position in the room," "We made fewer errors than other teams," "I was able to prevent errors from being made during the task," and so on). Statements were modified from items in the Networked Minds Measure of Social Presence [7] and NASA's Situational Awareness Rating Technique [37]. In addition, participants were asked to rate their feelings of closeness with their partner using the Inclusion of Other in the Self Scale [3].

Procedure

An experimenter greeted the participant at the entrance of our laboratory and obtained informed consent. The experimenter then seated the participant in front of a computer and gave the participant up to 10 minutes to practice either driving the telepresence robot around (in the mobile condition) or practice moving through a maze (in the stationary condition). Once 10 minutes had elapsed or the participant announced that they were finished with the practice, the experimenter disconnected the participant's terminal from the robotic telepresence system (in the mobile condition), instructed the participant on the construction task, and provided the participant with a picture of the finished object, as shown on the right in Figure 3. Following these steps, the experimenter reconnected to the robotic telepresence system and introduced the confederate as another participant in the study. The participant was reminded that they could begin when the timer was started and to open the door and announce when they were finished. After answering any questions, the experimenter started the timer and exited the room. During the task, the confederate did not initiate actions or provide guidance, acting only to complete participant instructions; this was to prevent affecting the speed of task completion or the number of mistakes. The confederate also limited her responses to a scripted list (e.g., "Like this?," "What next?," "Here?," "That's it? Great!") to maintain consistency across participants. Once the participant had opened the door of the experiment room and announced that the task was completed, the experimenter re-entered, turned off the timer, told the confederate to log out of the system, and administered the post-study questionnaire. Each session took approximately 30 minutes.

Participants

A total of 32 adults (four males and four females per condition), whose ages ranged between 18 and 30 years, M = 20.9, SD = 2.37, volunteered to participate in the study. We recruited from the University of Wisconsin–Madison campus community using online job postings and in-person recruitment. Participants reported that they were familiar with videoconferencing, M = 4.8, SD = 1.7 (1 = not very familiar, 7 = very familiar) and on average used videoconferencing once a month, M = 2.2, SD = 0.8 (1 = I did not use videoconferencing in the past 6 months, 2 = I used videoconferencing at least once a month in the past 6 months, 3 = I used videoconferencing at least once a week in the past 6 months, 4 = I used videoconferencing at least once a day in the past 6 months). Although we told participants that they would receive an extra dollar if they were the fastest team to complete the task correctly in order to motivate faster completion times, all participants received a total of $5, which included the completion bonus.

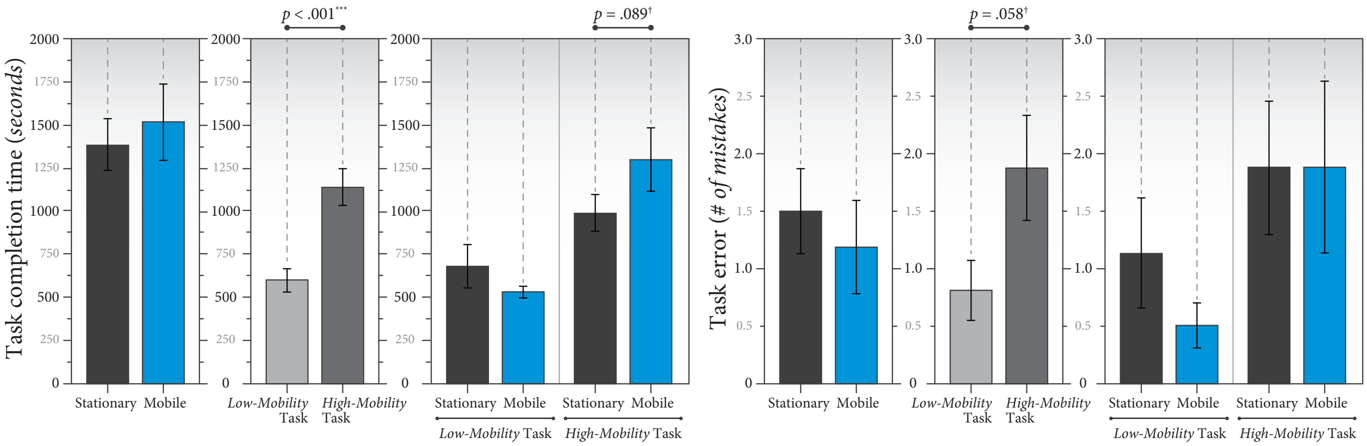

Figure 5. Data from measures of task completion time and task error. (***) and (†) denote $p < .001$ and $p < .10$, respectively. On the left, the high-mobility task took significantly longer to complete than the low-mobility task, and participants in the high-mobility task took marginally longer to complete the task when using the mobile vs. the stationary system. On the right, participants made marginally more mistakes in the high-mobility task than the low-mobility task.

Analyses

We tested age, gender, and videoconferencing experience as potential covariates and found that none had a significant effect ($p > .05$). A two-way fixed-effects analysis of variance (ANOVA) was conducted with the mobility of the system and task mobility requirements as input variables and completion time and number of mistakes as response variables. Planned comparisons in all tests used the Scheffé method. A Pearson's Chi-squared test was used to determine the effects of mobility on the participant's feelings of presence in the drawn map measure.

To construct scales from items in our questionnaire, we conducted an exploratory factor analysis, which resulted in four factors that corresponded to scales of teamwork (four items; Cronbach's $\alpha = .84$), team recovery (four items; Cronbach's $\alpha = .71$), workspace awareness (two items; Cronbach's $\alpha = .70$), and awareness of the environment (two items; Cronbach's $\alpha = .70$).

RESULTS

Our first hypothesis predicted that remote users would feel more present in the local environment when communicating with the confederate using a mobile system than when they used a stationary system. We found full support for this hypothesis; remote users reported themselves as present in the room with the confederate significantly more frequently when they used a mobile system than when they used a stationary system, $\chi^2(1, n = 31) = 8.7$, $p = .003$. A closer examination of these results showed that, when engaged in the low-mobility task, system mobility had no effect on feelings of presence, $\chi^2(1, n = 15) = .10$, $p = .73$. However, in the high-mobility task, all participants using a mobile system reported themselves as being present in the room with the confederate (where the object was being constructed), while all participants that used a stationary system reported themselves as being in a separate room (where they were physically seated), $\chi^2(1, n = 16) = 16.0$, $p < .001$. Figure 4 illustrates these results and provides examples of responses from participants who felt present in the room with the confederate and those who felt separate, i.e., present in the room where they were physically located.

Our second hypothesis posited that mobility would improve task performance in a high-mobility task but not in a low-mobility task. Our results did not provide support for this hypothesis. First, we found that it took participants significantly more time to complete the high-mobility task, $M = 1138.31$, $SD = 497.84$, than the low-mobility task, $M = 601.94$, $SD = 497.84$, $F(1, 28) = 18.57$, $p < .001$. There was also a marginal difference in the number of errors made between tasks, participants making more mistakes in the high-mobility task, $M = 1.88$, $SD = 2.15$, than in the low-mobility task, $M = 0.81$, $SD = 2.15$, $F(1, 28) = 3.91$, $p = .06$.

We found no main effect of system mobility on completion time or the number of errors. There was no significant difference in the time it took participants to complete tasks using the stationary system, $M = 829.50$, $SD = 497.82$, versus the mobile system, $M = 910.75$, $SD = 497.82$, $F(1, 28) = 0.43$, $p = .52$. There was also no significant difference between the number of errors made when the system was stationary, $M = 1.50$, $SD = 2.15$, versus when the system was mobile, $M = 1.19$, $SD = 2.15$, $F(1, 28) = 0.34$, $p = .57$.

However, we found that mobility had a marginal interaction effect between the mobility of the system and the mobility requirements of the task, $F(1, 28) = 3.39$, $p = .08$. The

Measure	F ratio	p value
Completion times		
System mobility	0.426 (1, 28)	.52
Task mobility	18.573 (1, 28)	.00***
System mobility × task mobility	3.389 (1, 28)	.08†
Mistakes		
System mobility	0.338 (1, 28)	.57
Task mobility	3.913 (1, 28)	.06
System mobility × task mobility	0.338 (1, 28)	.57†

Figure 6. Effects of system mobility and mobility required by the task on completion times and the number of mistakes. (†) and (***) denote $p < .10$ and $p < .001$, respectively.

high-mobility task took marginally longer when using the mobile system, $M = 1293.50$, $SD = 514.48$, than when using a stationary system, $M = 983.13$, $SD = 295.53$, $F(1, 28) = 3.11$, $p = .09$. There was no difference in the time it took participants to complete the low-mobility task between using the mobile system, $M = 528.00$, $SD = 94.50$, and the stationary system, $M = 675.88$, $SD = 367.03$, $F(1, 28) = 0.71$, $p = .41$.

We found no interaction effects for the mobility of the system and the mobility requirements of the task on the number of errors. Planned comparisons showed that participants using a mobile system made marginally more mistakes in the high-mobility task, $M = 1.88$, $SD = 2.10$, than in the low-mobility task, $M = 0.50$, $SD = 0.54$, $F(1, 28) = 3.28$, $p = .08$.

Finally, we found no significant effects of system mobility or the mobility required by the task on the remote user's perceptions of teamwork, team recovery, workspace awareness, and environmental awareness.

DISCUSSION

Consistent with our first hypothesis, our results showed that system mobility significantly improved the remote's feelings of being present in the local's location, particularly when the task required high levels of mobility. In these situations, we observed that all participants using the mobile system not only actively moved in the task space, but also exhibited more present behaviors. For instance, when constructing the large object, participants who were driving the system used language that referred to themselves in space, such as "Where am I?" and "I'm just trying to get into a position where I can see the corner." However, when using a stationary system or in the low-mobility task, we observed requests and statements by the remote user that referred to actions of the local confederate, such as "Can you push the object back please?" and "I can't see what you're doing, can you hold it up?"

Contrary to the predictions of our second hypothesis, greater mobility did not increase task efficiency or accuracy. Using a mobile system was actually detrimental to task performance in the high-mobility task and had no effect in the low-mobility task. We believe that the reasons for this outcome fall into two primary categories: a high burden of attention for the remote user and an instability in the remote user's frame of reference, which are discussed in the paragraphs below.

Burden of Attention

During the task, we observed a number of behaviors that seemed to indicate that participants found performing the task and maneuvering the telepresence robot to require high levels of attention. In their comments in the post-study survey, participants illustrated task difficulties with comments such as "It was hard to communicate everything you wanted to say using non-verbal actions and more directions verbally instead," "[It was] difficult describing connectors," and "I'm pretty horrible at this [the construction task]." Many users were unfamiliar with the shapes of the joints and had trouble articulating differences between pieces and directions for the construction. Participants also reported difficulties with translating the photograph into three dimensional space, sometimes resulting in an object that was a mirror image of the one in the instructions.

We also observed participants having difficulties with maneuvering the telepresence robot. Although users were given 10 minutes to train with the system and were provided with an instruction sheet explaining the controls (the four arrow keys on the keyboard for moving in four possible directions), users still experienced challenges. For example, participants were observed to back into walls, run into pipes on the ground, or to move extremely slowly to avoid collisions. These difficulties resulted in one user tipping the system over during the training period and crashing it, such that the system had to be recovered from a prone position on the floor.

In NASA's Situational Awareness Rating Technique (SART) [37], the primary factors for understanding a user's situational awareness include the user's division of attention, spare mental capacity, concentration, and familiarity with the situation. While each of these factors individually may not have been a problem for participants, our observations were that the combination of being presented with an unfamiliar control system, coping with the task, having to divide attention between the photograph and the video of the other room, the pressure of competing in time and accuracy, and the concentration needed to interact with the local confederate, may have been overwhelming for users in the mobile system condition. This high cognitive load may have resulted in an inability to take full advantage of the system's mobility, decreasing their ability to work quickly. This effect may have been particularly strong in the high-mobility task, as the low-mobility task did not require participants to move.

Instability of Reference Points

Psychological research on spatial cognition has studied the cognitive techniques that people use to understand their own positioning and the positioning of objects in their environment [27]. In this work, spatial reference systems are divided into three categories, *egocentric reference systems*, where location is specified with respect to the observer, *environmental reference systems*, in which locations are specified with respect to other objects, and *intrinsic reference systems*, when people learn a particular spatial layout of objects or a pattern [27]. This work provides strong evidence that memories of room-sized layouts are mentally represented in terms of egocentric reference systems (e.g., to my left [10]) or intrinsic reference systems, particularly when objects may be grouped into higher-order clusters [27].

In our task, when participants were not able to maneuver around the environment, their frame of reference was fixed in an egocentric view, where their spatial understanding was limited to object positioning in relation to the robotic telepresence system, or "themselves." However, when the mobility of the system enabled participants to change their field of view, their mental model for understanding object positioning may have changed to an intrinsic reference system. This may have led them to attempt to gauge where objects were in relation to other features in the environment (e.g., "the red piece behind the chair"), causing problems for the three reasons discussed below.

First, the system provided the remote user with a narrow field of view, making it challenging for participants to see multiple objects at a time. As a result, once the participant had moved in space, relating new objects to old ones became increasingly difficult. During the high-mobility task, participants using the mobile system occasionally asked the confederate for help in relating the objects that they could see at that moment with the locations that they had previously been, (e.g., “Is this the orange piece from the corner you just added the green thingy to?” and “Wait, is this the one across from the red pipe?”).

Second, when physically present, people may rely on a number of environmental and kinesthetic cues to estimate their changes in position. In the robotic telepresence system that we used, no feedback was provided for how far the system had rotated or the distance that it had moved, creating distortions in egocentric frames of reference. Exacerbating this situation was our decision to remove all distinguishing characteristics from the study room in order to minimize distractions from the task at hand. While there were several features (such as doors, windows, and furniture) which would be common in an office or factory setting, the environment was not as rich in cues as more naturalistic settings might be. We observed participants in the mobile condition moving the system forward, then pausing to turn back and forth to get a better understanding of their position and surroundings. In some cases, participants would back up to their previous position and make remarks such as “Ok, so that’s there...” before driving forward again, leading us to the conclusion that they were searching for objects in the environment to use as navigational aids. We also observed occasions in which the participant rotated the system and lost track of how far they had gone, ending in their facing a wall and having to ask the confederate, “Where are you now?”

Third, the most distinguishing objects in the room were the pieces for constructing the object and the confederate. As required by the task, both the pieces and the confederate were in constant movement under the direction provided by the participant. When using the stationary system, we often observed participants referring to the confederate’s position when the confederate was not in view of the camera, as in the statements “There should be a green joint on your left and a red one on your right...” and “Yeah, right where you are now.” In contrast, when using a mobile system, participants appeared disoriented about the confederate’s location in relation to their own, leading to backing repeatedly into walls while trying to locate the confederate or the object.

Previous work in computer-mediated communication has identified that the remote user’s inability to understand how they are situated in the local user’s environment can cause problems or frictions between users [21]. When viewed from the perspective of robotic telepresence systems, this lack of positional awareness significantly limits the ability of these systems to support task collaboration and has the potential to render them unusable. While the ability to navigate has shown dividends in creating an orientation-free mental representation of the environment versus an orientation-dependent representation developed from a map or photographs [35], our results highlight the gap between having the ability to move and the user actually benefitting from the capability.

One potential solution for supporting the remote user’s navigational needs is to leverage heads-up displays to create a realistic three dimensional representation of a virtual environment, such as a recreation of the local’s surroundings, and to simulate a correct perspective for the user by monitoring the relative position of the user’s eyes or head [25, 4]. However, head mounted displays introduce other challenges for users of robotic telepresence systems, as they obfuscate the remote user’s face.

DESIGN IMPLICATIONS

Our findings suggest that while the addition of mobility may provide remote users with a greater sense of presence in the local’s environment, simply providing them with the ability to maneuver is not enough. The ability to drive the telepresence system not only adds the burden of understanding its spatial positioning in relation to other objects in the environment, but also divides the remote user’s attention, significantly increasing cognitive load. Walking and talking becomes a much more difficult proposition when trying to interact with others through a mobile system.

While these problems are not insurmountable, our research points to the need for designers to consider ways of supporting the remote user’s efforts. For example, providing the remote user with a wider field of view may allow them to gain a better intrinsic understanding of the location of obstacles in the environment. Adding indicators in telepresence interfaces that show the distance traveled, the degrees of rotation turned, or the position of the telepresence robot on a simple map of the local environment, such as those provided in gaming interfaces, may aid in maintaining an egocentric view of the system’s position. Providing the remote user with the ability to offload the controls for movement, either by providing pre-planned paths or more intuitively mapped control systems, such as game or gesture-based controllers, may reduce cognitive load, allowing the remote user to more fully focus on the task at hand.

LIMITATIONS AND FUTURE WORK

Based on our study, we believe that there are informative lessons learned and fruitful paths forward for future work. First, to control for the difficulty of maneuvering the robotic telepresence system, it is critical for future studies to provide a flexible training period that allows participants to become comfortable and agile with the system. This lengthened training period would enable achieving a certain skill level instead of training for a set period of time. Alternatively, a longer-term study could examine task performance over time. Second, to be able to make broader claims about the use of robotic telepresence systems in spatially-oriented tasks, it is important for future work to explore a wider variety of tasks, such as collaborative exploration, search and rescue, and so on. Third, providing a richer, more naturalistic environment with stable reference points, such as additional furniture or wall hangings, may not only improve overall task performance with the robotic telepresence system, but may also offer greater external validity. While we chose to use a commercial system for our study to more accurately simulate real-world conditions, the use of a custom system in follow-up studies would allow greater latitude for a deeper investigation into how mobility might best be supported. Furthermore, there are always limitations of a study's participant pool in terms of how representative it is of a broader population of people with diverse educational, professional, and cultural backgrounds, which may be addressed by conducting follow-up studies, e.g., across different professional environments or cultural contexts. For this purpose, we have sought to provide sufficient detail in the Methods Section to allow future repeatability of our study.

CONCLUSION

Our work explored the effects of mobility on collaborative outcomes in two different task scenarios—a "small" task that required low levels of mobility and a "large" task with high mobility requirements—seeking to answer the question, "When does mobility matter?" To this end, we conducted a controlled laboratory experiment that followed a two-by-two (system mobility: stationary vs. mobile; task mobility requirements: low vs. high) between-participants design in which participants acted as the remote user and a confederate acted as the local user. Our results showed that the mobility of the system significantly improved the remote user's feelings of presence, particularly in tasks requiring high levels of mobility. However, contrary to our prediction, we found that mobility lowered task performance in measures of efficiency in high-mobility tasks. Our results suggest that, although the ability to maneuver the system provides remote users with immediate benefits such as a greater sense of presence, there is an often overlooked burden that controlling a mobile system adds to the remote user's cognitive load. These findings not only have implications for creating awareness of the potential consequences of providing the remote user with additional functionalities, such as mobility, but also highlight new opportunities for designing tools to support remote users. Robotic telepresence systems offer the unique chance to participate in and to directly contribute to physically situated tasks. However, our findings highlight the need for a deeper understanding of how mobility may be integrated in the design of robotic telepresence systems to best support the demands that such tasks place on the remote users.

ACKNOWLEDGMENTS

We would like to thank Jilana Boston, Brandi Hefty, and Ross Luo for their help with conducting the study. This research was supported by National Science Foundation award 1117652.

REFERENCES

1. Adalgeirsson, S. O., and Breazeal, C. Mebot: a robotic platform for socially embodied presence. In *Proc. of the 5th ACM/IEEE international conference on Human-robot interaction*, HRI '10, IEEE Press (Piscataway, NJ, USA, 2010), 15–22.
2. Anybots, Inc. Qb, 2012 (accessed September 8, 2012). https://www.anybots.com.
3. Aron, A., Aron, E. N., and Smollan, D. Inclusion of other in the self scale and the structure of interpersonal closeness. *Journal of personality and social psychology 63*, 4 (1992), 596.
4. Arthur, K. W., Booth, K. S., and Ware, C. Evaluating 3d task performance for fish tank virtual worlds. *ACM Transactions on Information Systems (TOIS) 11*, 3 (1993), 239–265.
5. Baker, M., Hansen, T., Joiner, R., and Traum, D. The role of grounding in collaborative learning tasks. *Collaborative learning: Cognitive and computational approaches* (1999), 31–63.
6. Beer, J. M., and Takayama, L. Mobile remote presence systems for older adults: acceptance, benefits, and concerns. In *Proc. of the 6th international conference on Human-robot interaction*, ACM Press (2011), 19–26.
7. Biocca, F., Harms, C., and Gregg, J. The networked minds measure of social presence: pilot test of the factor structure and concurrent validity. *Media Interface and Network Design Lab* (2001).
8. Brush, A. B., Meyers, B. R., Scott, J., and Venolia, G. Exploring awareness needs and information display preferences between coworkers. In *Proc. of the 2009 annual conference on Human factors in computing systems*, ACM Press (2009), 2091–2094.
9. Chen, M. Leveraging the asymmetric sensitivity of eye contact for videoconference. In *Proc. of the 2002 annual conference on Human factors in computing systems*, ACM Press (2002), 49–56.
10. Diwadkar, V. A., and McNamara, T. P. Viewpoint dependence in scene recognition. *Psychological Science 8*, 4 (1997), 302–307.
11. Double Robotics. Double, 2012 (accessed September 8, 2012). http://www.doublerobotics.com/.
12. Doucette, A., Mandryk, R. L., Gutwin, C., Nacenta, M., and Pavlovych, A. The effects of tactile feedback and movement alteration on interaction and awareness with digital embodiments. In *Proc. of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, ACM (New York, NY, USA, 2013), 1891–1900.
13. Dourish, P., and Bellotti, V. Awareness and coordination in shared workspaces. In *Proc. of the 1992 ACM conference on Computer-supported cooperative work*, CSCW '92, ACM (New York, NY, USA, 1992), 107–114.
14. Ellis, C. A., Gibbs, S. J., and Rein, G. Groupware: some issues and experiences. *Commun. ACM 34*, 1 (Jan. 1991), 39–58.
15. Fels, D. I., Waalen, J. K., Zhai, S., and Weiss, P. Telepresence under exceptional circumstances: Enriching the connection to school for sick children. In *Proc. Interact 2001* (2001), 617–624.
16. Fong, T., and Thorpe, C. Vehicle teleoperation interfaces. *Autonomous robots 11*, 1 (2001), 9–18.
17. Giraff Technologies AB. Giraff, 2012 (accessed September 8, 2012). http://www.giraff.org/om-giraff/.
18. Grudin, J. Groupware and social dynamics: eight challenges for developers. *Commun. ACM 37*, 1 (Jan. 1994), 92–105.

19. Gutwin, C., and Greenberg, S. The effects of workspace awareness support on the usability of real-time distributed groupware. *ACM Trans. Comput.-Hum. Interact. 6*, 3 (Sept. 1999), 243–281.

20. Gutwin, C., and Greenberg, S. A descriptive framework of workspace awareness for real-time groupware. *Computer Supported Cooperative Work (CSCW) 11*, 3-4 (2002), 411–446.

21. Heath, C., and Luff, P. Disembodied conduct: communication through video in a multi-media office environment. In *Proc. of the 1991 annual conference on Human factors in computing systems*, ACM Press (1991), 99–103.

22. Kraut, R. E., Fish, R. S., Root, R. W., and Chalfonte, B. L. Informal communication in organizations: Form, function, and technology. In *Human reactions to technology: Claremont symposium on applied social psychology*, Citeseer (1990), 145–199.

23. Lee, M. K., and Takayama, L. "Now, I have a body": uses and social norms for mobile remote presence in the workplace. In *Proc. of the 2011 annual conference on Human factors in computing systems*, ACM Press (2011), 33–42.

24. McGovern, D. E. Human interfaces in remote driving. Tech. rep., Sandia National Labs., Albuquerque, NM (USA), 1988.

25. McKenna, M. Interactive viewpoint control and three-dimensional operations. In *Proc. of the 1992 symposium on Interactive 3D graphics*, ACM (1992), 53–56.

26. Michaud, F., Boissy, P., Corriveau, H., Grant, A., Lauria, M., Labonte, D., Cloutier, R., Roux, M., Royer, M., and Iannuzzi, D. Telepresence robot for home care assistance. In *Proc. of AAAI Spring Symposium on Multidisciplinary Collaboration for Socially Assistive Robotics* (2007), 50–56.

27. Mou, W., and McNamara, T. P. Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition 28*, 1 (2002), 162.

28. Nakanishi, H., Murakami, Y., Nogami, D., and Ishiguro, H. Minimum movement matters: impact of robot-mounted cameras on social telepresence. In *Proc. of the 2008 ACM conference on Computer supported cooperative work*, CSCW '08, ACM (New York, NY, USA, 2008), 303–312.

29. Paulos, E., and Canny, J. Prop: personal roving presence. In *Proc. of the 1998 annual conference on Human factors in computing systems*, ACM Press (1998), 296–303.

30. Rae, I., Takayama, L., and Mutlu, B. One of the gang: supporting in-group behavior for embodied mediated communication. In *Proc. of the 2012 annual conference on Human factors in computing systems*, ACM Press (2012), 3091–3100.

31. Rae, I., Takayama, L., and Mutlu, B. In-body experiences: embodiment, control, and trust in robot-mediated communication. In *Proc. of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, ACM (New York, NY, USA, 2013), 1921–1930.

32. Rae, I., Takayama, L., and Mutlu, B. The influence of height in robot-mediated communication. In *Proc. of the 8th ACM/IEEE international conference on Human-robot interaction*, HRI '13, IEEE Press (Piscataway, NJ, USA, 2013), 1–8.

33. RoboDynamics. Luna, 2012 (accessed September 8, 2012). http://robodynamics.com/.

34. Suitable Technologies. Beam, 2012 (accessed September 15, 2013). https://www.suitabletech.com/beam/.

35. Sun, H.-J., Chan, G. S., and Campos, J. L. Active navigation and orientation-free spatial representations. *Memory & Cognition 32*, 1 (2004), 51–71.

36. Tang, A., Pahud, M., Inkpen, K., Benko, H., Tang, J. C., and Buxton, B. Three's company: understanding communication channels in three-way distributed collaboration. In *Proc. of the 2010 ACM conference on Computer supported cooperative work*, ACM Press (2010), 271–280.

37. Taylor, R. Situational awareness rating technique(sart): The development of a tool for aircrew systems design. *AGARD, Situational Awareness in Aerospace Operations 17 p(SEE N 90-28972 23-53)* (1990).

38. Toshima, I., Aoki, S., and Hirahara, T. Sound localization using an acoustical telepresence robot: Telehead ii. *Presence: Teleoperators and Virtual Environments 17*, 4 (2008), 392–404.

39. Tsui, K., and Yanco, H. Assistive, rehabilitation, and surgical robots from the perspective of medical and healthcare professionals. In *AAAI 2007 Workshop on Human Implications of Human-Robot Interaction*, Technical Report WS-07-07 Papers from the AAAI 2007 Workshop on Human Implications of HRI (2007).

40. Tsui, K. M., Desai, M., Yanco, H. A., and Uhlik, C. Exploring use cases for telepresence robots. In *Proc. of the 6th international conference on Human-robot interaction*, ACM Press (2011), 11–18.

41. Venolia, G., Tang, J., Cervantes, R., Bly, S., Robertson, G., Lee, B., and Inkpen, K. Embodied social proxy: mediating interpersonal connection in hub-and-satellite teams. In *Proc. of the 2010 annual conference on Human factors in computing systems*, ACM Press (2010), 1049–1058.

42. VGo Communications, Inc. Vgo, 2012 (accessed September 8, 2012). http://www.vgocom.com/.

43. Weeks, G. D., and Chapanis, A. Cooperative versus conflictive problem solving in three telecommunication modes. *Perceptual and motor skills 42*, 3 (06/01; 2012/09 1976), 879–917.