Handheld or Handsfree? Remote Collaboration via Lightweight Head-Mounted Displays and Handheld Devices

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ABSTRACT

Emerging wearable and mobile communication technologies, such as lightweight head-mounted displays (HMDs) and handheld devices, promise support for everyday remote collaboration. Despite their potential for widespread use, their effectiveness as collaborative tools is unknown, particularly in physical tasks involving mobility. To better understand their impact on collaborative behaviors, perceptions, and performance, we conducted a two-by-two (technology type: HMD vs. tablet computer; task setting: static vs. dynamic) between-subjects study where participants ($n = 66$) remotely collaborated as "helper" and "worker" pairs in the construction of a physical object. Our results showed that, in the dynamic task, HMD use enabled helpers to offer more frequent directing commands and more proactive assistance, resulting in marginally faster task completion. In the static task, while tablet use helped convey subtle visual information, helpers and workers had conflicting perceptions of how the two technologies contributed to their success. Our findings offer strong design and research implications, underlining the importance of a consistent view of the shared workspace and the differential support collaborators with different roles receive from technologies.

ACM Classification Keywords

H.5.3 **Information Interfaces and Presentation**: Group and Organization Interfaces–*Collaborative computing, Computer-supported cooperative work, Evaluation/methodology*

General Terms

Human Factors; Performance; Experimentation

Author Keywords

Computer-supported cooperative work; remote collaboration; videoconferencing; head-mounted displays (HMDs); wearable computing; handheld devices; tablet computers

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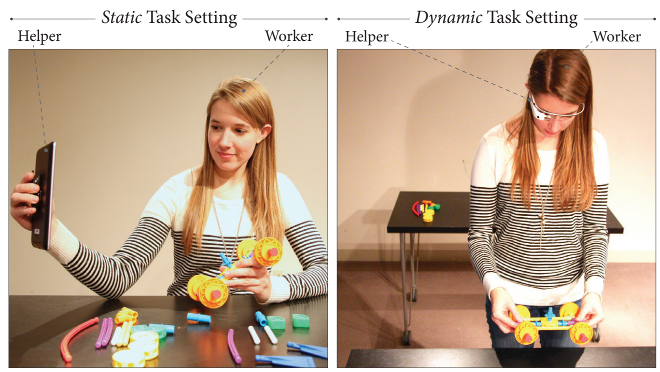

Figure 1. Participants remotely collaborated in pairs using either a tablet or an HMD in a construction task in one of two task settings: a *static* task setting, requiring low levels of mobility, or a *dynamic* task setting, requiring high levels of mobility.

INTRODUCTION

Collaborative work across many domains involves physical tasks. A team of doctors performing surgery, workers repairing machinery, and young adults learning how to cook from their parents are examples of hands-on activities where the level of expertise differs across members of the collaboration. Distributed physical tasks, in which not all members of the collaboration are collocated, have important roles in medical, industrial, and educational domains. With the rapid development of communication and collaboration technologies that enable remote workspace sharing, such as smartphones, tablets, and lightweight head-mounted displays (HMDs), remote collaboration for physical tasks has become more feasible than ever. These technologies promise easy assistance to users from their co-workers, family members, or friends who have expertise in their task—not just those individuals who are most geographically accessible.

While many technologies that support assistance in physical tasks are finding widespread use, little research has been conducted to evaluate their efficiency and effectiveness in these settings. One class of collaboration technologies are handheld mobile devices, such as smartphones and tablet computers, which are equipped with videoconferencing capabilities that can enhance collaboration [8]. Tablets are also becoming increasingly popular for both work and casual use [9]. The larger screen size of a tablet computer relative to the smartphone may also prove beneficial for supporting collaborative activities. One real-world example of tablet usage is a theatre company which provided each of its troupes with a tablet to hold video conferences with managers located at company headquarters, reducing the costs of emergency travel [21]. Other instances of tablet use involve the receipt of instructions by repair technicians in the field and the relay of video footage of furniture products from warehouse staff to purchasing agents to ensure product quality [32].

Lightweight HMDs constitute another class of technologies which hold promise for supporting remote physical collaboration. These devices are emerging as a commercially available family of products that people use for collaboration to link and work seamlessly with other mobile and wearable technologies. While the concept of a head-mounted display is not new [43], these emerging lightweight HMDs are designed to be smaller and less obtrusive relative to eariler immersive HMDs [12]. Lightweight HMDs are designed to provide information in a minimal fashion, which links them more closely to the physical environment than to a virtual environment [31]. This closer connection to the real environment while emphasizing less the augmentation of reality may make lightweight HMDs better suited than immersive HMDs to supporting communication and collaboration. Similar to smartphones and tablet computers, there is limited research evaluating the effectiveness of lightweight HMDs in supporting remote collaboration on physical tasks.

Given the growing availability of remote collaboration tools, a better understanding of how these tools support collaboration in physical tasks is required to inform the design of collaboration tools and to help predict collaborative outcomes. Furthermore, it is important to understand how these technologies impact collaborative outcomes under a variety of task conditions. One such condition is the level of *mobility*—the ability to physically move freely and easily—required by the task. Different tasks require different levels of mobility of the collaborators (see Figure 1). Repairing a large piece of machinery requires a worker to be very mobile, whereas performing surgery involves focused work with low mobility. We expect there to be tradeoffs involved with different technologies providing a better fit for collaborations with different goals and task requirements.

Prior work evaluating remote collaboration technologies has focused almost exclusively on tasks requiring low levels of mobility [13, 14, 29]. For example, Fussell et al. [14] compared a scene camera and a camera integrated in a bulky HMD and found that the scene-oriented display outperformed the HMD in a low-mobility task. However, whether these findings would generalize to handheld mobile devices or lightweight wearable devices is unclear. How these findings generalize to tasks requiring high levels of mobility also remains unexplored.

Our objective in this work is to begin to fill this gap by investigating how the design features of two different technologies, a handheld tablet computer and a lightweight HMD, affect collaborative outcomes for remote collaboration on physical tasks under task settings requiring differing levels of mobility. These technologies were chosen because mobile handheld computers have found widespread use in many domains [11, 22, 35], and lightweight HMDs are emerging as a handsfree alternative to handheld computers [47]. We seek to inform the design of future collaborative technologies and to highlight the strengths and weaknesses of the technology types in various collaborative settings, explaining these differences using concepts from prior work including shared visual space [13] and conversational grounding [5].

The next section provides an overview of related work on supporting remote physical collaboration and previous evaluations of technologies in similar collaboration settings. This section is followed by a description of our hypothesis and study design. We then present the results of our study and discuss our findings and their implications for the design and evaluation of future remote collaboration technologies.

RELATED WORK

In order to understand how different technologies can support collaborative outcomes, it is important to identify the aspects of collaboration that are most critical to its success. Prior work on supporting remote collaboration has focused on the importance of a *shared visual space*—the ability of collaborators to have simultaneous visual access to the task space being worked in—and on supporting *conversational grounding*—the process of establishing common ground to reach mutual understanding [3].

Shared Visual Space

Previous work identifies a shared visual space between collaborators as a key factor contributing to the success of their collaboration [14] because it provides an awareness of the task state [18]. The shared visual space can be divided into two categories: a shared view of the task space and a shared view of the collaborator.

Previous work found that participants perform better in side-by-side settings in which they share views of the workspace rather than when they use communication tools to complete a task [13, 15, 20, 28, 33]. Fussell et al. [13] conducted an experiment with collaborators working over an audio/video link or working side-by-side. They found that collocated pairs completed the task more quickly and accurately than pairs working remotely and cited the shared task space as a contributing factor to the difference. Prior work has found shared visual space to help collaborators understand the current state of their task and enable them to communicate more efficiently [28]. Daly-Jones et al. [8] compared videoconferencing to high-quality audio conferencing and identified a shared visual space as the most important resource for effective communication.

Research on videoconferencing and audio conferencing has also found that videoconferencing can enhance collaboration by providing a view of the collaborator to convey other visual information including gestures, posture, and facial expressions [25]. Tasks that rely heavily on social cues, such as situations of conflict, have been shown to be especially affected by the visual view of the collaborator [2, 16, 40]. This work suggests that technologies that provide support for the shared visual task space and view of the collaborator result in more effective collaboration than technologies that do not.

Conversational Grounding

Conversational grounding has been found to be a critical factor in many types of efficient collaborations [3]. Fussell et al. [15] found that communication is demonstrably more efficient when people share greater amounts of common ground. Studies of the process collaborators follow to establish common ground during physical tasks demonstrate the following pattern between a helper (the expert) and a worker [5, 6, 15, 19]. First, the collaborators use referential expressions to form common ground about the task steps. The helper next instructs the worker on how to manipulate the objects needed for the task and then verifies that they understood the instructions and are executing them correctly. These acts of conversational grounding build up a level of common ground that is necessary for the communication of beliefs and intentions [45].

How this grounding process takes place also depends on the communication medium itself. The chosen medium of communication imposes costs on the grounding process and shapes how conversations will be conducted over the medium [5]. Prior work has shown that mutual belief can be achieved much faster in face-to-face conversations compared with mediated ones [4]. Kraut et al. [29] argued that the medium affects how collaborators communicate and speak about the task, indicating that the choice of communication medium directly affects collaborators' ability to establish common ground and to communicate intentions.

Technological Support for Collaboration

A growing body of work has evaluated the effectiveness of emerging technologies to support collaboration. This work has examined collaborations employing a variety of new technologies, including large multi-touch displays [1, 27, 38] and tabletops [7, 24, 39]. Other work has examined remote collaborations using these technologies, studying how distributed tabletops may support gesture use [17], how virtually embodying users' arms affects coordination on distributed tabletops [10], and how design guidelines for non-distributed tabletop settings may extend to distributed tabletops [26]. These technologies are not mobile and generally necessitate user collocation around the display for collaboration. Furthermore, collaboration on large displays and tabletops primarily involves the manipulation of digital artifacts, providing little support for collaborations over physical artifacts.

Fewer studies have focused on understanding how emerging mobile technologies support remote collaboration in the context of physical tasks. Poelman et al. [34] examined how an immersive HMD allowed an expert to remotely assist a novice in a crime scene investigation task. Their system provided the remote expert and the novice with the ability to add and remove virtual artifacts from a map of the environment visible to the novice via the HMD. They found that their system supported mutual understanding of the task state between the collaborators. Similar work has explored supporting collaboration with other augmented reality techniques, such as projecting the expert's gestures into the worker's workspace [23, 41]. To study collaboration on shared geocaching over distance, Procyk et al. [36] used a system consisting of a wearable mobile video camera mounted on a pair of glasses and a smartphone on an armband for displaying live video from the other user's camera. They found that their mobile system was able to create an intimate shared experience with the remote partner. Rae et al. [37] studied the effects of mobility on the task performance of robotic telepresence users. They investigated whether the mobility of the system was more useful in tasks requiring higher levels of mobility. They found that mobility in general increased remote users' sense of presence but did not improve task performance, even impairing it in some cases due to the added burden of understanding spatial positioning in the remote environment. Fussell et al. [14] conducted an experiment in which dyads performed a collaborative task to determine the most effective medium to support remote collaboration among audio, scene video, head-mounted video, and combined scene and head-mounted video. They found that a scene camera achieved better results than a head-mounted camera because it provided a more consistent view of the shared visual space [8]. However, this work only considered static tasks (e.g., assembling a toy robot in a stationary position). Additionally, the authors noted that the HMD slipped off of participants' heads, and that HMDs at the time the study was conducted were not "robust enough for actual field applications" [14].

To bridge the gap in previous work examining the impact of task mobility on collaborative outcomes across communication technologies, our study compares the collaborative outcomes of users in a remote physical task using either of two emerging technologies—a tablet computer or a lightweight HMD—in tasks requiring either high or low levels of mobility.

HYPOTHESIS

Previous work found that a static camera achieved better results in a collaborative task than a head-mounted camera in static task settings, demonstrating the importance of providing collaborators a consistent view of the shared visual space [14]. Informed by this research, we formed our hypothesis on how communication technology and the mobility required by the task will affect collaborative outcomes—how collaborators behave, perceive the collaboration, and perform. We expect different technologies to be better suited to different task settings, to provide different degrees of consistency of the shared visual space, and to support collaboration differently in these settings. Specifically, we predict that the HMD will provide a more consistent view of the workspace during a dynamic task—a task requiring high levels of mobility—and that this increased view of the shared visual space will improve collaborative outcomes. Furthermore, we also predict that the tablet will provide a more consistent view of the worker's workspace in a static task setting—a task requiring low levels of mobility—which will lead to an increased view of the shared visual space and improve collaborative outcomes.

> **Hypothesis:** There will be a significant interaction effect of technology type and task setting on the behavioral, perceptual, and performance dimensions of collaboration. Specifically, the HMD will provide better support for these outcomes than the tablet in dynamic task settings, while the tablet will provide better support than the HMD in static task settings.

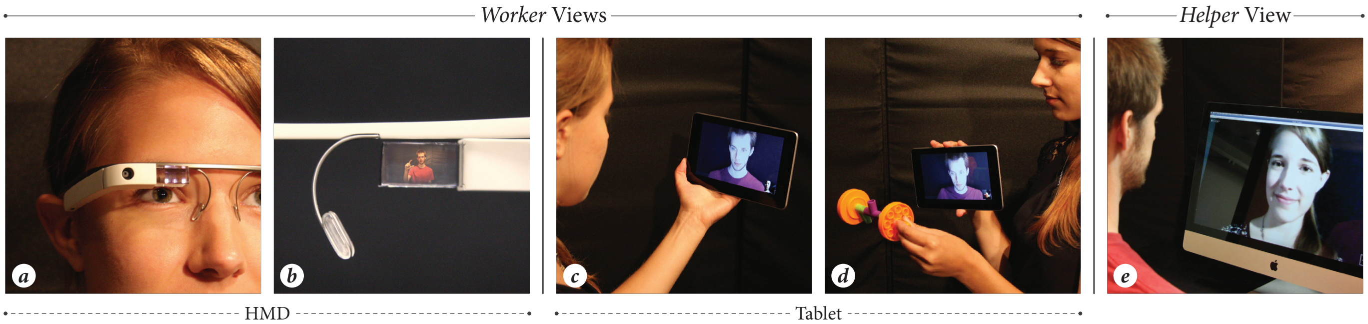

Figure 2. The capture (A) and display (B) using the HMD. The head-mounted camera on the HMD was used to provide live video to the remote helper, and the HMD display showed only the remote helper and no viewfinder. The display (C) and capture (D) using the tablet in two commonly used methods. Workers used the front-facing tablet camera to show the helper themselves or their workspace, and the tablet display showed the remote helper and a small viewfinder. The display (E) of the helper's computer, showing the worker.

METHOD

To test our hypothesis, we designed an experiment in which dyads worked together on a remote construction task similar to experimental tasks used in prior work (e.g., [14, 15, 29, 37]). In our study, participants were instructed to work together to make a toy cart. For each dyad, one participant played the role of the "worker," physically constructing the object with the assistance and guidance of another participant, the "helper," who was given a schematic detailing the cart's construction.

Participants

We recruited 66 participants (34 males and 32 females) to take part in the study. Participants were recruited in pairs and did not know each other before the study. All participants were native English speakers recruited from the University of Wisconsin–Madison campus. Participant ages ranged 18–35 ($M = 21.8$, $SD = 3.8$). Based on post-task questionnaire results, participants were overall comfortable using technology. On a five-point scale (1 = very uncomfortable, 5 = very comfortable), participants averaged 4.74 ($SD = 0.81$) on comfort using a laptop, 3.91 ($SD = 1.06$) on comfort using a tablet, and 4.03 ($SD = 0.81$) on comfort using videoconferencing software.

Study Design

We designed a two-by-two (technology type: HMD vs. tablet computer; task setting: static vs. dynamic) between-subjects study to examine the effects of technology type and task setting on measures of the behavioral, perceptual, and performance dimensions of collaboration.

The first independent variable we considered was technology type. Following prior approaches (e.g., [14]), we picked two devices designed for widespread use and investigated their support for collaboration at a system level, rather than using prototypes, the elements of which (camera, viewfinder, etc.) we could manipulate. Workers used either a *Google Nexus 7 tablet*[1] (7 in / 17.8 cm in screen size, 10.6 oz / 300 g in weight) in the *tablet* condition or wore *Google Glass*[2] (1.8 oz / 50 g in weight) in the *HMD* condition to collaborate with their partner. The Nexus 7 tablet was used because it is a representative example of modern tablet computers, and Google Glass was used because it is an example of an emerging commercially-available lightweight HMD. Because we wanted to examine differences in collaborative outcomes between mobile devices in mobile settings, no stand or propping device was provided with the tablet.

In each technology condition, the interaction took place using a browser-based videoconferencing application called *Google Hangouts*.[3] The use of the same videoconferencing software standardized the interface design for helpers and workers in both technology conditions. The helper used a 27" desktop computer equipped with a webcam and microphone for videoconferencing, regardless of the worker's device. Both the camera and display functionalities of the Nexus 7 tablet and Google Glass were used to support the videoconferencing interactions. Figure 2 shows the display and camera configurations for both devices and demonstrates how the videoconferencing user interface was shown on the devices. The tablet videoconferencing interface displayed a view of the remote collaborator and a small "viewfinder" pane, showing what the tablet camera was capturing. As shown in the bottom-right corner of the tablet images in Figure 2C and 2D, the tablet viewfinder pane was very small, measuring less than 2.2% of the area of the tablet screen. Additionally, as shown in Figure 2D, the screen of the tablet and the viewfinder in the interface were not always visible to workers during the task. The HMD interface displayed a view of the remote collaborator as well, but did not show a viewfinder pane. The helper's desktop interface displayed the video captured from the worker's device camera and a viewfinder pane.

The second independent variable we considered was the task setting. In the *static* setting, the necessary components to construct the object were separated into three groups located on a single workstation in the worker's room. In the *dynamic* setting, the component groups were placed on three workstations spaced several feet apart throughout the room. Participants were not allowed to carry more than one individual unconstructed piece between piles. This restriction ensured that participants did not treat the dynamic task as a static one by consolidating piles. Video recordings of the collaboration were reviewed to ensure the success of the task-setting manipulation. The dynamic setting represents many physical

[1] http://www.google.com/nexus/7/

[2] http://www.google.com/glass/

[3] http://www.google.com/hangouts/

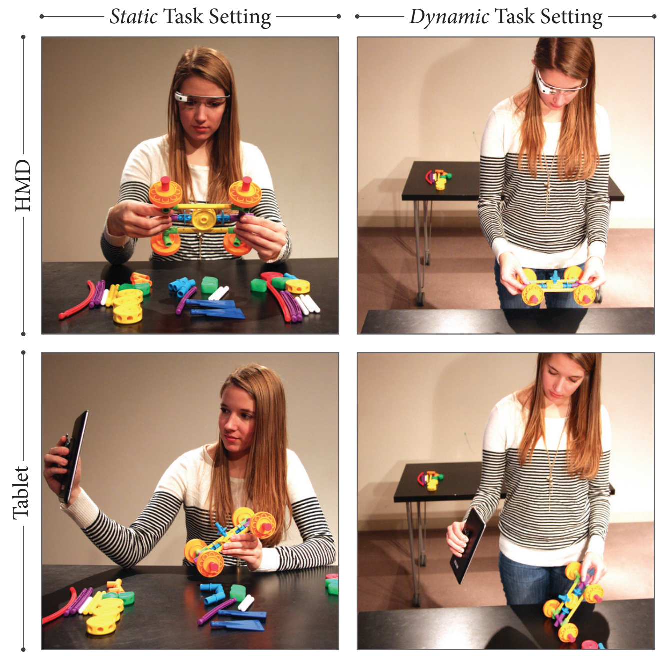

Figure 3. The worker's environment across the four conditions of our study. Participants collaborated using either an HMD (top row) or a tablet (bottom row) in a task setting requiring either low levels of mobility (left column) or high levels of mobility (right column).

collaboration settings where tools and parts are distributed throughout the environment, such as in a kitchen or a workshop. In both conditions, not all of the pieces in the piles were necessary to construct the object. Figure 3 illustrates the worker's environment across the four conditions.

Setup and Materials

The following paragraphs describe the construction task and the setup of the study.

Setup — Figure 4 shows the layout of the worker's and helper's rooms for each task setting. In both the static and dynamic task settings, the helper and worker were located in different rooms during the construction task. The setup for the helper, as illustrated in the center of Figure 4 and the left of Figure 5, was the same across all conditions. The setups for the worker in static and dynamic task settings are also depicted on the left and the right in Figure 4, respectively. In the static task setting, all of the components were located in three piles on a single workstation in the worker's room, whereas in the dynamic task setting, they were distributed between three workstations in the room. Each pile included parts for various components of the target object to increase the mobility required of the participants as they switched between piles during the task.

Task — The right side of Figure 5 shows the toy cart used as the basis for the construction task. The cart was selected for its moderate level of construction difficulty. The completed cart contained 48 components of various sizes and colors.

Schematic — A schematic showing three overarching construction steps and an image of the completed object was given to the helpers for use in guiding the workers to construct the cart. The schematic was printed in color and marked components which needed repeated construction, such as sections of the wheels and axles. Helpers were not allowed to show their partner any part of the schematic.

Measurement

To measure the behavioral, perceptual, and performance dimensions of collaboration during the task, we used a number of behavioral, subjective, and objective measures.

Collaborative Behavior — Participant pairs were video-recorded collaborating on the task, and the videos were coded for high-level conversational events, including:

- Helper proactive assistance
- Helper reactive assistance
- Helper high-level directing commands
- Helper view commands
- Helper questions about the task
- Worker questions about the task

These codes measured conversational acts of collaborators that constituted a majority of the speech acts occurring during the task. Many of these codes were selected for their use in prior work (e.g., [29]). We coded the videos for both proactive and reactive helper assistance, differentiated by whether or not the helper's description or statement was in response to a previous speech act of the worker. We also coded the recordings for high-level *directing* commands from the helper. These

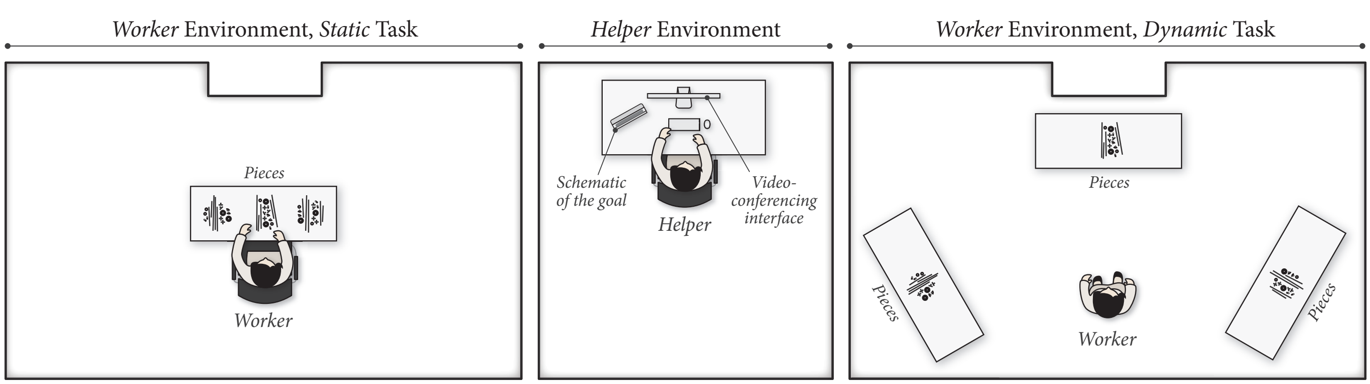

Figure 4. The physical arrangements of the worker's room in the static task condition (left), the helper's environment in both conditions (center), and the worker's room in the dynamic condition (right).

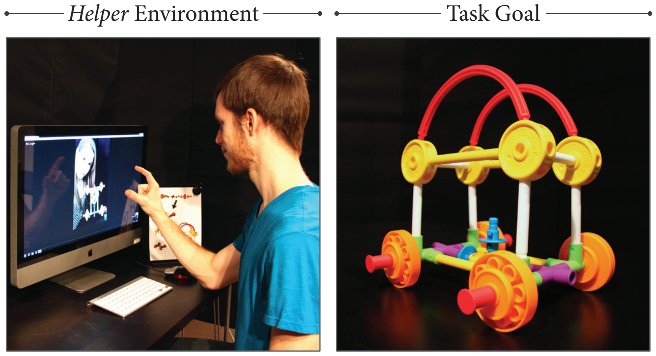

Figure 5. ***Left:*** **the helper at the remote workstation.** ***Right:*** **the completed cart.**

commands involved defining an objective, and often require subsequent sub-commands, clarifications, or other assistance to ensure that the action is properly executed. We also coded the videos for helper *view* commands, which are commands to the worker to adjust the orientation of their device to offer the helper a more desirable view of the workspace.

The coding process involved a single experimenter coding all videos and a second experimenter coding 10% of the videos in order to verify the reliability of the coding process. An inter-coder reliability analysis showed substantial agreement between the experimenters (87% agreement, Cohen's $\kappa = .79$).

Collaborative Performance — Two measures of task performance were considered during the experiment: completion time and error rate. To measure completion time, the the experimenter started a timer after instructing the participants to begin the task and then exiting the room. The timer was stopped when a participant knocked on the door or opened it and informed the experimenter that they believed they had finished the task. After the task was completed, the video was coded for errors. An error was counted if (1) a part that wasn't required for the construction was used or (2) a part required for the construction was used in the wrong place.

Collaborative Perceptions — Two questionnaires, one for each experimental role (helper and worker), were administered after the completion of the task. The questionnaires each contained 14 questions designed to capture participants' perceptions of the success of their collaboration. Items such as "I am confident we completed the task correctly" and "My partner and I worked well together on the task" were used to create a scale of the perceived overall success of the collaboration. Role-specific questions were also used. For instance, helpers were asked, "I could tell when my partner needed assistance." Correspondingly, workers were asked, "My partner could tell when I needed assistance." Responses to all items were measured on a five-point rating scale (1 = Strongly disagree, 5 = Strongly agree). Reliability tests for these scales are provided in the Analyses Section. Additionally, the questionnaires included a brief section collecting basic demographic information such as age, gender, and major/occupation and assessing participants' overall level of comfort with technology use.

Procedure

For this study, two participants were recruited at once to form dyads. An experimenter randomly assigned one participant to the role of helper and the other to the role of worker. Each dyad was randomly assigned to one of the four conditions. The experimenter then obtained informed consent and briefed the participants on the selected technology and the constraints of the task setting. If the dyad was assigned to the static task setting, the experimenter told the participants that the worker was required to remain seated at the workstation. If they were assigned to the dynamic task setting, participants were told that the worker was not allowed to move parts from a workstation unless the parts had already been assembled or the worker was carrying only a single piece. This restriction ensured that participants did not treat the dynamic task as a static task by consolidating piles of pieces. To provide participants with an incentive to work together efficiently, the experimenter told the participants that the team with the fastest task completion time of a correct object would each receive an extra dollar, similar to the incentive mechanism used by Rae et al. [37]. The participants were then separated into different rooms based on their experimental roles to receive individual instructions.

After the participants were separated, the experimenter gave the worker specific instructions on how to use their assigned technology type. The experimenter then moved to the other room, showed the helper the videoconferencing interface on the desktop computer, and gave the helper time to examine the schematic of the cart. The experimenter then enabled the videoconferencing connection between the participants, waited for a moment to ensure that the connection was stable, and told the participants that they could begin the task. Audio and video from the experiment were recorded for coding of behavioral measures. Once one of the participants opened the door to their experiment room and indicated that they finished the task, the experimenter re-entered the helper's room, turned off the timer, terminated the videoconferencing connection, and administered the post-task questionnaire. The experimenter then re-entered the worker's room and administered the post-task questionnaire. Upon the completion of the questionnaires, participants were debriefed together by the experimenter. Each session took approximately 30 minutes. Participants were each paid $5.00 USD for their time. Additionally, although participants were told that members of the fastest team would receive an extra dollar to incentivize them, all participants received the additional compensation.

Analyses

A two-way fixed-effects analysis of variance (ANOVA) was conducted with task setting and technology type as input variables and the behavioral, objective, and subjective measures as response variables. Following Wickens and Keppel [46], we calculated *a priori* contrast tests to make comparisons indicated by our hypothesis.

To construct scales from the items in our questionnaires, we conducted an exploratory factor analysis, which resulted in two factors—one for each participant role—that corresponded to scales of perceptions of overall collaborative success. The helpers' scale consisted of two items (Cronbach's $\alpha = .851$), and the workers' scale consisted of five items (Cronbach's $\alpha = .841$). Our analysis also included a single item for workers' ease of seeing the helper.

RESULTS

Guided by our hypothesis, our analysis primarily involved testing for interaction effects between technology type and task setting and for differences between technology types for each task setting across the behavioral, perceptual, and performance dimensions of collaboration that we measured. We also tested for main effects of technology type to better understand the overall effects these technologies had on collaboration. Our analyses used an alpha level of .05 for significance. We also report on marginal effects at an alpha level of .10 to illustrate trends in our data. Effect sizes are reported as eta-squared (η^2) values. To facilitate readability, the paragraphs below provide only a textual description of the results and a discussion of them in the context of our hypotheses and the specific characteristics of the study. The results for the statistical tests we conducted are provided in Table 1, and the results for the contrast tests are provided in Table 2.

Across the behavioral and perceptual dimensions of collaboration, our results revealed several interaction effects of technology type and task setting on measures of proactive assistance, reactive assistance, helpers' perceptions of collaborative success, and workers' perceptions of collaborative success, demonstrating that the task setting affected users of the technologies differently. We found that in the dynamic task setting, HMD use allowed helpers to offer faster directing commands and more proactive assistance, resulting in marginally faster task completion times. In the static task setting, tablet use helped convey subtle visual information, and helpers and workers had opposing perceptions of how the two technologies contributed to their success. These findings provide support for the first portion of our hypothesis, which predicted the interaction effects between technology type and task setting shown by our analyses.

Our hypothesis predicted that the HMD would outperform the tablet in measures of collaborative outcomes in dynamic task settings, and we found support for this prediction in the behavioral and performance dimensions of collaboration. Data from measures of proactive assistance, reactive assistance, rate of directing commands given, and task completion time provide support for the HMD improving these collaborative outcomes in dynamic task settings.

As illustrated on the left in Figure 6, our results showed that helpers offered significantly more proactive assistance in both static and dynamic task settings and marginally less reactive assistance in dynamic task settings when collaborating via the HMD compared to the tablet. There was no significant difference in the total amount of assistance between technologies in dynamic conditions. We believe that this shift from reactive to proactive assistance is potentially very beneficial. A greater amount of helper proactive assistance indicates that helpers are better able to see when their partner requires help and to ground their directing commands to assist them accordingly. A simultaneous reduction in the quantity of reactive assistance is also beneficial, as it again shows that assistance is being offered without the worker need to ask for it, further attesting to the superior view of the task space the HMD appears to provide in these settings. Because of this shift in the

Behavioral Measures

Amount of *Proactive* Assistance

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	29.64	<.001 ***	0.488
Environment type	1	0.14	.711	0.002
Technology type × Environment type	1	2.95	.096 †	0.048
Error	29			

Amount of *Reactive* Assistance

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	0.01	.935	0.000
Environment type	1	0.01	.959	0.000
Technology type × Environment type	1	6.95	.013 *	0.193
Error	29			

Helper *Directing* Commands/Minute

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	4.05	.054 †	0.102
Environment type	1	6.15	.019 *	0.155
Technology type × Environment type	1	0.29	.595	0.007
Error	29			

Helper *View* Commands/Minute

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	3.68	.065 †	0.107
Environment type	1	1.56	.222	0.045
Technology type × Environment type	1	0.00	.996	0.000
Error	29			

Perceptual Measures

***Helper* Perceptions of Overall Success**

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	1.31	.263	0.066
Environment type	1	4.66	.039 *	0.118
Technology type × Environment type	1	4.66	.039 *	0.118
Error	29			

***Worker* Perceptions of Overall Success**

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	1.36	.254	0.035
Environment type	1	0.64	.430	0.017
Technology type × Environment type	1	7.78	.009 **	0.201
Error	29			

Ease of Seeing Partner for *Worker*

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	5.44	.028 *	0.194
Environment type	1	0.01	.911	0.000
Technology type × Environment type	1	0.49	.492	0.014
Error	29			

Performance Measures

Task Completion Time

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	2.81	.104	0.068
Environment type	1	8.45	.007 **	0.203
Technology type × Environment type	1	0.79	.381	0.019
Error	29			

Error Rate

Source of Variation	*Df*	*f*	*p*	η^2
Technology type	1	0.00	.965	0.000
Environment type	1	0.04	.840	0.001
Technology type × Environment type	1	0.13	.719	0.005
Error	29			

Table 1. ANOVA test results for the behavioral, perceptual, and performance dimensions of collaboration.

Measure *Group* **A**	*Group* **B**	*Mean* **A**	*SD* **A**	*Mean* **B**	*SD* **B**	*p*
Behavioral Measures						
Amount of *Proactive* Assistance						
Dynamic, HMD	Dynamic, Tablet	3.25	2.61	1.22	0.97	.011*
Static, HMD	Static, Tablet	4.38	1.30	0.50	0.54	<.001***
Amount of *Reactive* Assistance						
Dynamic, HMD	Dynamic, Tablet	3.25	2.32	5.78	2.49	.061†
Static, HMD	Static, Tablet	5.75	3.92	3.38	1.30	.086†
Amount of *Total* Assistance						
Dynamic, HMD	Dynamic, Tablet	6.50	4.00	7.00	2.78	.759
Static, HMD	Static, Tablet	10.13	4.26	3.88	1.64	<.001***
Helper *Directing* Commands/Minute						
Dynamic, HMD	Dynamic, Tablet	1.85	0.51	1.55	0.52	.294
Static, HMD	Static, Tablet	2.46	0.54	1.95	0.72	.084†
Helper *View* Commands/Minute						
Dynamic, HMD	Dynamic, Tablet	0.33	0.19	0.17	0.14	.180
Static, HMD	Static, Tablet	0.43	0.35	0.27	0.19	.190
Perceptual Measures						
***Helper* Perceptions of Overall Success**						
Dynamic, HMD	Dynamic, Tablet	4.75	0.38	4.50	0.50	.472
Static, HMD	Static, Tablet	3.69	0.46	4.50	1.19	.029*
***Worker* Perceptions of Overall Success**						
Dynamic, HMD	Dynamic, Tablet	4.13	0.60	4.53	0.40	.253
Static, HMD	Static, Tablet	4.63	0.31	3.63	1.23	.010*
Worker Ease of Seeing Partner						
Dynamic, HMD	Dynamic, Tablet	3.63	1.19	4.56	0.73	.039*
Static, HMD	Static, Tablet	3.88	0.99	4.38	0.52	.269
Performance Measures						
Task Completion Time						
Dynamic, HMD	Dynamic, Tablet	801.00	194.50	1004.56	321.90	.076†
Static, HMD	Static, Tablet	640.88	198.30	703.38	137.90	.587
Error Rate						
Dynamic, HMD	Dynamic, Tablet	1.88	2.23	1.56	2.79	.772
Static, HMD	Static, Tablet	1.75	1.98	2.00	1.77	.826

Table 2. Contrast test results for the behavioral, perceptual, and performance dimensions of collaboration.

type of the assistance offered, workers may not need to ask for verification of correctness as frequently during their tasks. These results suggest that HMD use, especially in dynamic task settings, may result in a more fluid collaboration and fewer interruptions for verification of task status.

Our results also showed that helpers gave directing commands at a marginally higher rate in HMD conditions than in tablet conditions, and there was no significant difference in the total number of directing commands given between conditions (see Figure 6, right). Furthermore, as is shown on the right in Figure 7, pairs collaborating using the HMD achieved marginally faster task completion times than those using a tablet in dynamic task settings. These results suggest that HMD use supports marginally more efficient collaborations than a tablet computer when the task requires higher levels of mobility. Based on these results, we predict HMDs to be more effective than tablets for achieving efficient and fluid collaboration in dynamic task settings, improving both collaborative behaviors and performance.

Our hypothesis also predicted that the tablet computer would outperform the HMD in measures of collaborative outcomes in static task settings. We found support for this prediction in the behavioral and perceptual dimensions of collaboration. Data from measures of rate of helpers' view commands, helpers' perceptions of collaborative success, and workers' ease of seeing their partner provide support for tablet use improving behavioral and subjective outcomes of collaboration.

As shown on the left in Figure 7, we found that helpers rated their perceptions of collaborative success significantly higher when their partner communicated with them using a tablet than an HMD in the static task setting. We believe that this difference results from the more consistent view of the current focus of the interaction that the tablet provided in the static setting. We observed workers using the tablet in the static condition working in two phases. In one phase, they sat the tablet on their workstation and constructed the cart. They performed the construction while either holding the components they were working with above the tablet such that the helper could observe their work or with the components outside of the helper's view. In the latter case, they sought verification by holding their work in front of the helper after completion. In the second phase, when searching for pieces, they picked the tablet up and held it such that the helper could see all of the piles of pieces at once or had the helper describe the piece needed and showed the helper pieces they thought matched the description. Pairs developed this workaround because they were unable to position the tablet such that it offered a complete and consistent view of their workspace. The tablet videoconferencing interface displayed a small view in the corner of the screen of what the helper was able to see from the tablet's camera, which allowed workers to ensure that the helper was able to see what they needed during both phases. These phases amount to the helper having two views and associated tasks to alternate between when using a tablet in the static setting—constructing and searching/describing. When their partner used an HMD in the static task setting, these two phases of the construction task were less distinct, possibly increasing helpers' cognitive load.

When pairs collaborated via the HMD, having the helper's view tied to the worker's head motions in the static task was at times detrimental. We found that helper commands to adjust the view were required marginally more frequently when using the HMD compared to the tablet, shown on the right in Figure 6. Unlike the tablet interface, the HMD interface offered no feedback to the worker regarding what the helper could see from their camera, requiring helpers to ask the workers to look down more when constructing the cart in static conditions because they were working with the object on the table too close to their body for the helper to see. Since workers were moving between stations in the dynamic condition, they held the cart more frequently during construction, providing helpers with more opportunities to see their work. We believe that the dependency of the camera view on the worker's head orientation combined with the lack of feedback given to the worker on what the helper could see when using an HMD led to helpers' reduced perceptions of success in static task settings. Tablet use may consequently improve aspects of collaborative perceptions in static task settings.

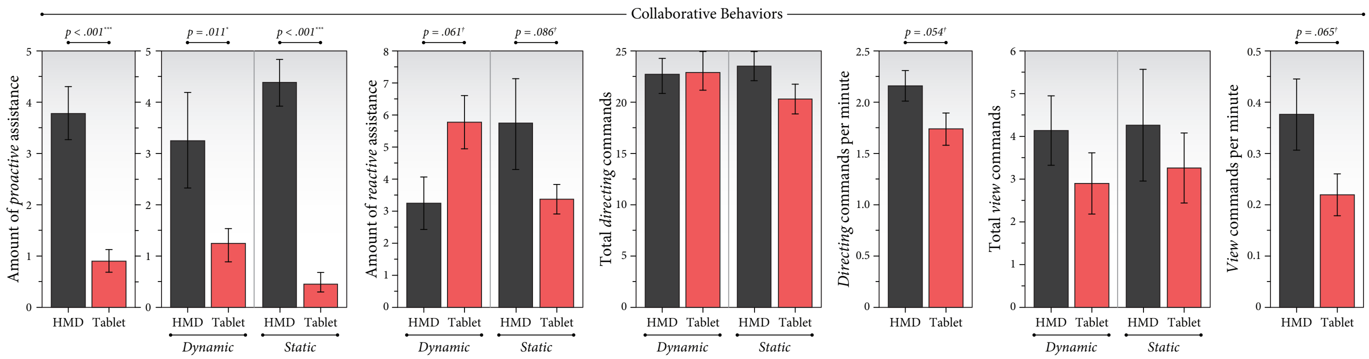

Figure 6. ***Left:*** **Amount of proactive and reactive assistance.** ***Right:*** **Data from coding of total directing commands, directing commands per minute, total view commands, and view commands per minute. (†), (*), and (***) denote $p < .10$, $p < .05$, and $p < .001$, respectively. Helpers gave significantly more proactive assistance in HMD conditions and marginally less reactive assistance when an HMD was used compared to when a tablet computer was used in dynamic task settings. Helpers also gave directing commands and view commands at a higher rate in HMD conditions than in tablet conditions. There were no significant differences in the total number of directing or view commands between conditions.**

Workers found it significantly easier to see their partner when using the tablet compared to the HMD (see Figure 7, left). This difference is likely due to the difference in the amount of visual information that is transferred between collaborators using the tablet compared with the HMD. Although the Google Glass display is closer to the worker, the Nexus 7 has a much larger screen than the Google Glass display. The Nexus 7's 1280 × 800 resolution display is also much more detailed than Google Glass' 640 × 360 display, and it is therefore likely a much better platform for conveying gestures, facial expressions, and other visual cues. We therefore anticipate that in situations where there is more than one expert providing assistance or when the worker would benefit from gestures or other visual cues from the expert, that a tablet, with its larger and more detailed display, will achieve better collaborative outcomes than an HMD or other devices with smaller screens.

Contrary to our hypothesis, we found that workers perceived their collaboration to be overall more successful when using the HMD compared to the tablet in the static task setting (see Figure 7, left). These perceptions could be explained by a novelty effect; when we gathered this data, Google Glass was not yet available to the public, so participants were especially enthusiastic to use the new technology. However, our results do not support this explanation, as we found no significant difference in workers' perceptions of overall success between the technologies in the dynamic task setting. Based on experimenter observations, we believe that workers perceived their collaboration as more successful when using the HMD during the static task because of the perceived "clunkiness" of their use of the tablet. As previously described, it was difficult for workers to place the tablet such that it offered a complete and consistent view of their workspace, so they alternated between the constructing and the searching/describing phases. While this method improved helpers' perceptions of the collaboration by offering them two views and associated tasks, it negatively affected workers' perceptions of task success by increasing the amount of work required to complete the task. This distinction suggests that technological workarounds during collaborative tasks may have a differential effect on the parties involved.

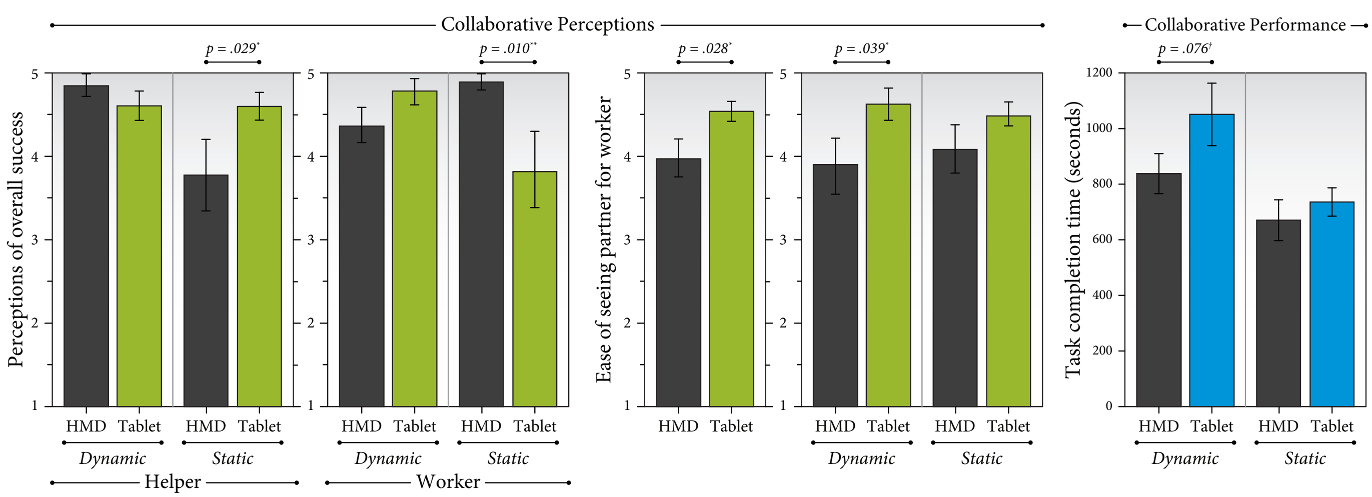

Figure 7. ***Left:*** **Mean scale responses of helpers' and workers' perceptions of the overall success of their collaboration and from workers' perception of the ease of seeing their partner.** ***Right:*** **Mean task completion times. (†), (*), and (**) denote $p < .10$, $p < .05$, and $p < .01$, respectively. In static task settings, helpers had significantly higher perceptions of collaborative success in the tablet condition, while workers had significantly higher perceptions of collaborative success in the HMD condition. Workers in tablet conditions had a significantly easier time seeing their partners, and pairs using an HMD completed the task marginally faster than pairs using a tablet in dynamic task settings.**

DISCUSSION

Our results offer many implications for research and for the design of future technologies for remote collaboration which we describe in the paragraphs below.

We found that helpers' perceptions of collaborative success were significantly lower when workers used an HMD compared to a tablet in the static task setting. This result highlights the importance of offering feedback to technology users about what their camera is capturing. This feedback is especially important for HMD users because the camera moves with its wearer's head. Many tablet, smartphone, and desktop videoconferencing interfaces offer a "viewfinder" showing what the device's camera is capturing. However, the HMD interface of Google Hangouts used in our study did not offer this feature. We speculate that this view was not included in the design of the HMD for three reasons. First, seeing a moving video as they move their head might be disruptive to the user's focus. Second, the only function for such a viewfinder would be to indicate to the wearer the extent of their camera view, of which wearers may build a mental model as they use the HMD for other purposes, such as recording videos. Third, because the resolution of the Google Glass display is relatively low (640×360 pixels), offering a large enough viewfinder that offers a similarly detailed view to other tablet or smartphone interfaces may be difficult. For these reasons, the videoconferencing interface was not replicated in the HMD conditions and the viewfinder was omitted.

To better allow remote helpers to gather the visual information they need, future HMD devices could be designed with a camera with a wider angle of view or with a camera whose orientation can be controlled by the remote collaborator. To offer a better view of the task space in static conditions, software could allow helpers to define the object of interest and to have the camera mounted on the HMD turn to keep that object in the field of view despite the wearer's head motions. Even without altering the hardware, it could also be beneficial to simply allow HMD users to alternate their display to show either their collaborator or the video feed from their camera to provide workers the necessary feedback to ensure that their helper can see what they need. As our results showed that the absence of this type of feedback may have had negative implications for collaborative perceptions, it will be important for designers of emerging collaborative technologies to consider how to best offer feedback to the user from their device's camera.

Our findings also suggest that collaborative technologies and their associated workarounds affect collaborative roles differently. We believe that future researchers and designers need to consider these differences when developing new technologies and interfaces for collaboration. For instance, when developing a new interface to support remote training of employees, one may be inclined to evaluate only how the interface affects employees' perceptions of the training experience. Given our finding that there may be tradeoffs in collaborative outcomes involved, it would also be important to evaluate how the interface affects the performance, behaviors, and perceptions of the remote trainers.

Our results confirm previous findings that highlight the importance of a consistent view of the shared task space as a significant factor affecting multiple dimensions of collaboration [8, 13, 28]. We found that the HMD offered a more consistent view of the task space in dynamic task settings and that this consistency improved collaborative behaviors by shifting assistance from reactive to proactive and collaborative performance by allowing pairs to complete the task marginally faster. Consistent with findings by Kraut et al. [28], our results show that the shared visual space helped collaborators ground their conversation and communicate more efficiently by marginally increasing the rate at which directing commands were given.

Our results demonstrate the importance of a consistent view of the shared task space. However, we believe that offering a view of the task space itself may not be enough to effectively support remote collaboration. Our results are from technology conditions where the view given to the remote helper also provides cues about the worker's current focus. The HMD closely ties the visual information given to the remote helper with the worker's focus by changing the view with the worker's head movements, which previous work has shown to be a reliable predictor of attention [30, 42]. Accordingly, as we chose to maintain the intended "mobile" characteristics of these devices and offered no stand or propping device for the tablet, the visual information given to the helper was the result of an intentional action of the worker picking up the tablet and specifically showing the helper their workspace and therefore provided cues for their focus. When seeking to disconnect the visual information provided to the remote helper from the worker's focus, such as when using a stand with a handheld device or when giving the remote user control of the camera mounted to an HMD, in addition to supporting the shared view of the workspace, providing remote helpers with other cues such as an indicator of worker focus may be important.

Limitations and Future Work

There are six key limitations of our study that reveal potential avenues for future research. First, the specific technology platforms used in our study likely affected our results. Using a lightweight HMD other than Google Glass may give different results. Similarly, we used a popular tablet computer, but using a larger tablet with a portable stand or a smaller mobile device that is easier to handle, such as a smartphone, might provide users with a different experience. Future replication studies with other platforms will inform us on whether or not these results are generalizable.

Second, the members of the dyads in our study were strangers, but collaborations often involve repeated interactions or established practices and rapport between collaborators. Based on prior work [44], we expect aspects of interactions, including how grounding occurs, to be different between colleagues than between strangers. Future work can examine how collaboration history affects the use and effectiveness of the communication medium across different task settings.

Third, our study examined how technology and task setting affected a single collaborative instance of a short duration.

People may change how they use technologies over time, discover additional workarounds, or find more effective ways of using them for their task. Future work can examine how technology supports repeated instances of collaboration or collaborations over time.

Fourth, the experts in our study were not true experts. They only had the schematic for the construction task. True experts will also know patterns in which people make errors, predict them during instruction, and offer more proactive suggestions and corrections. This difference may make a stronger case for HMD use, given our observation that it involved greater levels of proactive assistance.

Fifth, our experimental task was very tolerant to errors, and we only examined the total number of errors upon the completion of the task. Errors made during a task in an industrial setting could result in damages to expensive equipment. Similarly, errors in medical settings could result in loss of life. In such settings, measures of task performance other than total errors upon completion will be more relevant. Future work could use other task-specific measures of performance, such as errors made during the task or ranked errors that factor in the criticality of errors, to better represent how the technology supports collaboration in these settings.

Finally, our work took the Nexus 7 tablet computer and Google Glass as they were and used them as mobile systems that are designed for widespread use. This choice introduces limitations such as not being able to isolate the effects of the camera, display, or viewfinder. Future research might conduct more detailed investigations using modular prototype systems with which these specific elements can be manipulated. However, our study provides a first look at how these technologies support communication and collaboration at a system level.

CONCLUSION

Our work examined the effects of using two different emerging mobile and wearable computing technologies—a Google Nexus 7 tablet computer and Google Glass, a lightweight HMD—on collaborative behaviors, perceptions, and performance in tasks requiring differing levels of mobility. We examined these differences in a collaborative construction task in two task settings: a *static* condition, in which the components necessary for construction were located in a single workspace, and a *dynamic* condition, in which the components were distributed across multiple workspaces. We conducted a two-by-two (technology type: HMD vs. tablet computer; task setting: static vs. dynamic) between-participants study in which pairs of "helpers" and "workers" collaborated to construct an object. We found that in the dynamic task setting, HMD use allowed helpers to offer more frequent directing commands and more proactive assistance, resulting in marginally faster task completion times. In the static task setting, tablet use helped convey subtle visual information, and helpers and workers had opposing perceptions of how the two technologies contributed to their success. Our findings have implications for designers of collaborative systems, interfaces, and devices by highlighting the importance of offering a consistent view of the workspace and of providing feedback to technology users about the information they are giving to their remote collaborators. Our findings also demonstrate that the use of a collaborative technology and its associated workarounds affect collaborative roles differently, suggesting that future researchers and designers must consider these differences when developing new technologies or interfaces for collaborators.

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