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Visual Cues as Evidence of Others' Minds in Collaborative Physical Tasks

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Consider a surgical team in the midst of an operation. As the operation unfolds, the surgeon requires actions, such as the passing of surgical implements, on the part of the scrub nurse and other assistants. In order to coordinate their behavior, the surgeon and scrub nurse must mutually understand what surgical implement is needed at what time. One way they can coordinate is through language—the surgeon can simply say, for example, "Pass the scalpel." They can also communicate via gestures—the surgeon can point to the desired implement. Interestingly, however, observations of surgical teams have discovered that nurses often *predict*, by watching the surgeon's behaviors and the status of the task, what implements the surgeon needs and can have them ready in advance of any verbal or nonverbal requests (Nardi et al., 1993).

Surgical teams perform one example of a *collaborative physical task*, a task in which two or more individuals jointly perform actions on concrete objects in the three-dimensional world. Such tasks play an important role in many domains, including education, design, industry, and medicine. For example, an expert might guide a worker's performance of emergency aircraft repairs in a remote location, a group of students might collaborate to build a science project, or an emergency room team might combine its efforts to save a patient's life. In each case, the success with which group members can perform collaborative physical tasks depends to a large extent on how well they can infer one another's states of mind.

Observational studies of physical collaboration suggest that people's speech and actions are intricately related to the position and dynamics of objects, other people, and ongoing activities in the environment (e.g., Flor, 1998; Ford, 1999; Goodwin, 1996; Kuzuoka & Shoji, 1994; Tang, 1991). Conversations during collaborative physical tasks typically focus on identifying involved objects, describing actions to be performed on those objects, and confirming that the actions have been performed successfully. During the course of the task, the objects themselves may undergo changes in state as people act upon them (e.g., mechanical pieces of a device may become functional as it undergoes repair) or as the result of outside forces (e.g., a patient might start hemorrhaging).

The performance of collaborative physical tasks requires substantial coordination among participants' actions and talk. In face-to-face settings, much of this coordination is managed through visual information. Visual information plays at least two interrelated roles. First, it helps people maintain up-to-date mental models or *situation awareness* of the state of the task and others' activities (Endsley, 1995). This awareness can help them plan what to say or do next and to coordinate their utterances and actions with those of their partners. Second, visual information can help people communicate about the task, by aiding *conversational grounding*—the development of mutual understanding among conversational participants.

Actions and words are signs of state of mind, and they fluctuate in effectiveness depending on communication media and can substitute for one another in the grounding process. Our research explores relationships among visual information, conversational grounding, and the ability of communicators to understand each other's minds. We also explore the role of this mutual understanding in the collaborative process. Communicators' inferences about each other shape their decisions regarding how to situate, frame, and time their conversation about the task at hand.

In the remainder of this chapter we first describe how people collaborate on physical tasks—how they maintain situational awareness and ground their conversations. Then, we present our theoretical framework

for analyzing the role of visual cues in situational awareness and grounding. We next present an overview of our research paradigm and some selected findings regarding how visual cues are used to infer others' minds during collaborative physical tasks. We end with some conclusions about the role of visual information in inferring others' minds and directions for future research.

COLLABORATING ON PHYSICAL TASKS

In order for collaborators to provide useful assistance, they must determine what help is needed, when to provide the help, how to phrase their messages of assistance such that the worker understands them, and whether the message has been understood as intended or additional clarification is needed. That is, assistance must be coordinated not only with the worker's utterances but also with his or her actions and the current state of the task.

Consider the following fragment from a conversation in which a helper is telling a novice worker how to attach a bicycle saddle to its seat post using clamps.

HELPER: Now you want to fit the rails of the seat into that groove.

WORKER: I see. How can it fit into?

HELPER: You might want to unscrew those nuts a bit.

WORKER: Oh—OK.

HELPER: It will give you a little more room.

To have this dialogue, the helper needs to overcome several challenges. One challenge is for the helper to identify what the worker is attending to, in order to determine whether an object is part of the joint focus of attention. The helper's use of the definite article in "the rails" and "the seat" and deictic adjectives in "that groove" and "those nuts" depends on knowing the worker's focus of attention, to be assured that he was referring to the rails, seat, grooves, and nuts the helper was manipulating. A second challenge is to make sure that the worker understands an utterance before continuing the conversation. In this example, the worker verbally indicated understanding with phrases like "I see" or "OK." The helper could also infer understanding because he could see that the worker had indeed started to loosen the nuts. Finally, the helper needs to comply with Gricean norms of conversation, such as informativeness and brevity (Grice, 1975). In this case, he does so by using deictic references (e.g., "that groove") along with pointing.

One way helpers decide how to assist their partners is by maintaining *situation awareness* (Endsley, 1995)—a continually updated cognitive representation of the task and environment. Nardi and colleagues (1993) found that nurses continually monitor surgeons and patients to identify which surgical implement to provide. Likewise, in the bicycle repair task, helpers use their awareness of the state of the bicycle—what repairs have been made thus far, with what level of success—to determine what information to present next. One aspect of situation awareness is the awareness of what a partner is currently doing—what actions he or she is performing, with what tools and parts, and with what success. This information allows helpers to draw inferences about others' minds and to determine whether clarification or expansion of the instructions is required. If, for example, the worker is holding the wrong tool, the helper can interject a comment to correct this (e.g., "No, not that wrench, the larger wrench").

A second way helpers decide how to assist their partners is via conversation. As they present their instructions, helpers monitor workers' responses such as acknowledgments of understanding (e.g., "uh huh," "got it") and questions (e.g., "which wrench?"). Pairs work together to ensure that messages become part of their *common ground*, or shared knowledge and beliefs (Clark, 1996; Clark & Marshall, 1981; Clark & Wilkes-Gibbs, 1986). The term "grounding" refers to the interactive process by which communicators exchange evidence about what they do or do not understand over the course of a conversation, as they develop common ground (Clark & Brennan, 1991). Clark and Marshall (1981) identified three primary sources for grounding: membership in the same group or population (e.g., Fussell & Krauss, 1992; Isaacs & Clark, 1987), *linguistic co-presence* (the dialogue history), and *physical co-presence* (the shared physical setting). Shared views of objects and people are one important aspect of physical co-presence.

Visual cues provided by others' facial expressions, actions, and jointly observable task objects and environment can facilitate situation awareness and conversational grounding. (e.g., Daly-Jones, Monk, & Watts, 1998). In the operating room setting, nurses use visual cues to predict what surgeons will do next and what implements they will need (Nardi et al., 1993). Similarly, helpers in our bicycle repair task can monitor workers' facial expressions, workers' actions, and changes in the state of the bicycle, and tailor their instructions to ongoing changes in the workers' need for assistance. In the excerpt we gave previously, the helper used his observation that the worker was finished with a step to time his next instructions ("Now . . . "), and he used his view of the bicycle to determine that the nuts needed to be unscrewed. Similarly, because workers can view helpers' actions and hand movements, helpers

can use pointing gestures and deictic expressions (e.g., "that one") to refer quickly and efficiently to task objects. In the prior excerpt, the helper used a combination of pointing and a deictic expression, "those nuts," to refer effectively to the nuts in question.

Different types of visual cues vary in their importance for maintaining awareness and grounding conversation. For example, seeing a partner's facial expression gives evidence of his or her understanding but provides no information about the state of the task. A view of objects in the environment, in contrast, provides substantial information about the state of the task and indirect cues to others' understanding. A challenge, both for theoretical development and technology design, is to understand how people use specific types of visual evidence to make specific types of inferences about others' minds. What, for example, are the right visual cues to provide to doctors performing remote tele-surgery? Which cues are best for collaborating on an architectural design task across several physical locations?

We take a decompositional approach to this problem, in which we strive to specify the different types of visual information available to collaborators and identify how these cues influence inferences about others' minds, interpersonal communication, and task performance (Kraut, Fussell, Brennan, & Siegel, 2002). Our approach is illustrated in Table 6.1, in which we consider the types of inferences about others' minds that can be drawn from five sources of visual information—participants' faces, participants' head positions and gaze, participants' bodies and

TABLE 6.1. Types of Inferences That Can Be Drawn about Others' Minds Based on Five Types of Visual Cues

Type of visual evidence	Inferences about others' minds
Participants' faces	Facial expressions and nonverbal behaviors can be used to infer level of comprehension, emotional responses.
Participants' head positions and eye gaze	Eye gaze and head position can be used to establish others' general area of attention and infer intended actions.
Participants' bodies and actions	Body position and actions can be used to establish others' focus of attention; appropriateness of actions can be used to infer comprehension.
Task objects	Changes to task objects can be used to infer what others have done.
Work environment	Traces of others' actions may be present in the environment.

actions, the focal task objects, and the work environment. The table is intended to be illustrative of our approach rather than definitive; future research will be needed to fully specify the rows and columns of this table.

When two people are working side by side, they have all five sources of visual information easily available. If the participants have to collaborate across a distance, they must communicate through some type of telecommunications, substantially limiting the shared visual information. Although technology can be a hindrance to smooth interaction, the features of technology allow us to examine how visual evidence affects situation awareness and conversational grounding in ways that are not possible in face-to-face settings. In the next section, we discuss some of our studies of how people make use of visual cues to infer others' minds in collaborative physical tasks.

EMPIRICAL STUDIES OF VISUAL CUES IN COLLABORATIVE PHYSICAL TASKS

To investigate issues of others' minds in collaborative physical tasks, we use experimental paradigms in which pairs work together to perform a task such as repairing a bicycle, building a large toy robot, or completing an online jigsaw puzzle. In each of these tasks, one participant (the "worker") is responsible for manipulating pieces and tools; the other participant (the "helper") provides guidance but does not actually manipulate pieces or tools. The helper is provided with instructions for the task by way of a manual or diagram of the completed project. The task is thus similar to many learning environments, such as teachers instructing students, remote experts guiding vehicle repairs, or tele-surgery.

Within this basic paradigm, we manipulate features of the technologies that the pairs use as they complete the task and compare communication and performance with these technologies to side-by-side and audio-only control conditions. Dependent measures include task performance time, task errors, responses to survey questions about the success of the collaboration and perceptions of the value of the technologies, conversational coding of session transcripts, and, in some cases, more detailed analysis of the videotapes of the sessions.

To date, we have undertaken approximately a dozen studies of communication during collaborative physical tasks (e.g., Fussell, Kraut, & Siegel, 2000; Fussell, Setlock, & Kraut, 2003; Fussell et al., 2004; Gergle, Kraut, & Fussell, 2004a, 2004b; Gergle, Millen, Kraut, & Fussell, 2004; Kraut, Fussell, & Siegel, 2003; Kraut, Gergle, & Fussell, 2002; Kraut, Miller, & Siegel, 1996). Not surprisingly, these studies have consistently demonstrated that conversational grounding is most efficient and performance is best when pairs work side by side and share full visual co-presence. More interestingly, the visual cues provided by most (but not all) video technologies improve grounding and performance over audio-only connections. From our quantitative and qualitative analyses of interactions across different media conditions, we have found substantial evidence to support our theory that video enhances communication and performance by allowing both helpers and workers to use visual cues to infer each other's states of mind. Communicators rely on visual information to understand their partners' changing situations, needs, and priorities.

Evidence That Helpers Infer Workers' Minds

We first consider how visual cues influence helpers in collaborative physical tasks. Our quantitative analyses and more qualitative evaluations of the videotapes from the sessions lead us to propose that helpers make at least three types of inferences based on visual evidence. First, they make inferences about workers' mind states: for example, how busy they are, what their focus of attention is, and whether they understood the instructions. Second, they make more general inferences about worker's abilities—for example, whether they are adept at mechanical tasks or possess the cognitive skills required to perform successfully. Finally, they make inferences about the state of the task—how far along it is, how smoothly things are progressing, and whether or not any emergency situations have arisen. We find that these inferences shape the content and timing of helpers' instructions and their decisions about when to provide additional information or clarifications.

One example we see repeatedly in our videos is helpers' use of visual evidence to infer workers' comprehension of instructions. When they can see workers' actions, helpers provide verbal feedback on the correctness of those actions (e.g., "that's right"). Figure 6.1 shows verbal acknowledgments of behavior in the puzzle experiment. When they can see the worker, even if it is at a delay, helpers provide ongoing feedback about the correctness of those actions; when they can't see the worker, they provide no feedback at all. This suggests that visual cues from others' actions allow people to make inferences about how well they have understood instructions.

Appropriately timed interruptions also provide evidence that the helper is taking into account the worker's state of mind. In a version of our puzzle studies where the pairs used a text-chat client to converse about the task, we saw several instances of the helper having prepared his or her next message and having it ready to be sent. However, when timing was critical and the helper could visually monitor the work space,

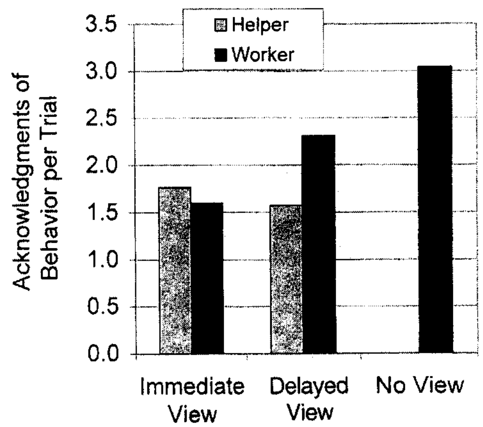

FIGURE 6.1. Acknowledgments of behavior in a collaborative puzzle task as a function of the participant's role and the helper's view of the worker. Data from Gergle et al. (2004).

he or she sometimes waited to send it so that it was received at the appropriate moment (i.e., at a less interruptible time when the partner could attend to the message and when the message matched a particular state of the puzzle).

Evidence That Workers Infer Helpers' Minds

Although the helper's view of the workspace varies with communication medium, the worker's view remains constant across conditions. Thus, if workers failed to attend to helpers' states of mind, they should behave in an identical fashion in all conditions. Instead, we find that workers use the knowledge they have about what helpers can see to infer what helpers know about workers' mind states, abilities, and the state of the task. For example, workers provide different sorts of feedback to helpers depending upon what helpers can see. As shown in Figure 6.2, workers provide significantly more acknowledgments (e.g., "OK," "I got it") when they know that the helper can't see them. When the helper can see the work area, workers are aware that the helper is watching and provide less explicit feedback about comprehension. Similarly, workers use more deictic expressions (e.g., "this one," "here") or pronouns to refer to task objects and locations when they think the helper can see them (side by side or via video) than when the helper is connected by audio only (Figure 6.3).

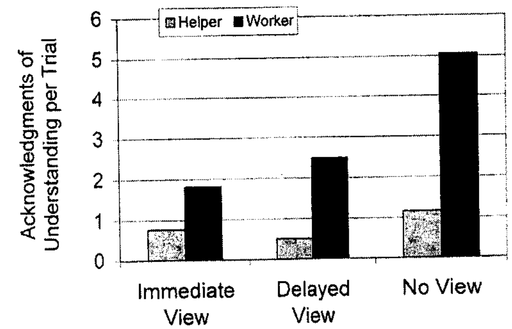

FIGURE 6.2. Acknowledgments of understanding in a collaborative puzzle task as a function of the participant's role and the helper's view of the worker. Data from Gergle et al. (2004).

A compelling example of this behavior can be seen in self-interruptions. In one example, the worker states, "Is it this . . . errr, the one with the black swatch on the right and two green . . . err . . . light green stripes . . . near the top?" In the first part of this utterance, the worker begins to form a deictic reference ("Is it this [one]?") but quickly remembers that the helper cannot see their workspace and replaces it with a more detailed description of the piece (" . . . errr, the one with the black swatch . . . ").

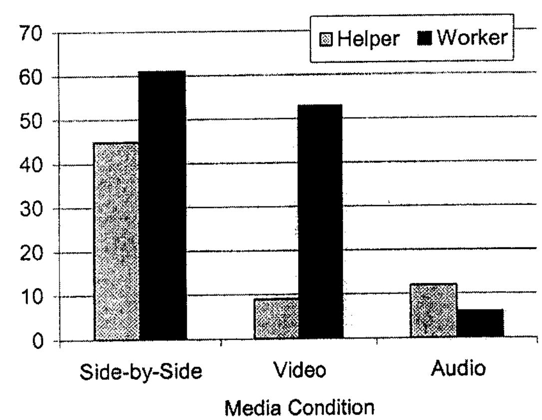

FIGURE 6.3. Use of deixis in a bicycle repair task as a function of media condition. Data from Kraut et al. (2003).

Sources of Evidence about Others' Minds

Results such as those reviewed above clearly demonstrate that visual cues allow communicators to infer each other's knowledge and establish common ground. But which visual cues are most important? In a recent study (Fussell, Setlock, & Parker, 2003), we examined where helpers look as they provide their instructions during a collaborative robot construction task. Helpers wore a helmet with an eye-tracking device during the study. We coded the onset and offset of gaze toward a set of targets: the workers' hands, the workers' faces, the robot being built, the set of task parts and tools, and the instruction manual. We then examined the gaze patterns for regularities that might help us understand how helpers make inferences about workers' mind states.

Our results indicated that helpers looked predominantly at the workers' hands, the robot pieces, and the robot under construction. They looked significantly less at the workers' faces (Figure 6.4). In addition, helpers appeared to use a regular sequence of glances across targets as they provided their instructions. Typically, they first looked at the robot and the manual to determine the next instruction; then, after giving their instructions, they looked at the workers' hands and the robot to

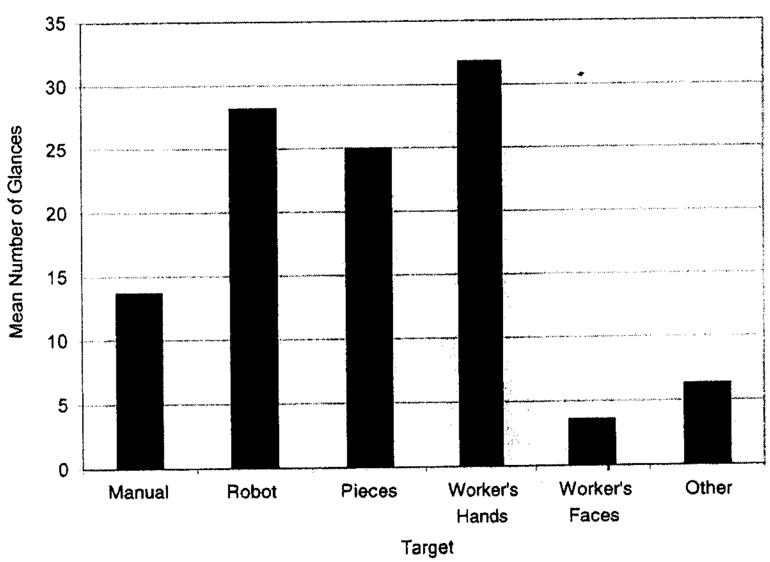

FIGURE 6.4. Mean number of helper glances by target during a collaborative robot construction task. Data from Fussell et al. (2003).

make sure the directions were being followed correctly. The findings support our hypothesis that helpers in collaborative physical tasks draw inferences about workers' mind states by watching what they do and assessing the appropriateness of their actions rather than by observing their facial expressions.

Actions as Evidence of Others' Minds

The results of our gaze tracking study suggest that helpers watch what workers *do* in addition to listening to what they *say* during collaborative physical tasks. The ensuing inferences shape the instructions and feedback they give. In face-to-face settings, much of the worker's contribution to the grounding process may be via his or her actions, as in the following example from our robot construction task:

HELPER: Alright, uh, take the orange thing.

WORKER: (*Picks up the orange dome.*)

HELPER: And, uh, um, one of these little pieces, that one right there.

WORKER: (*Picks up small black piece.*)

HELPER: Put it, uh, on the underside of the orange dome on the left.

WORKER: (*Drops piece, picks it up, connects it to the bottom of the dome.*)

HELPER: Yeah, like that.

We are currently applying sequential modeling to better understand how participants interweave verbal messages and behaviors in the grounding process (e.g., Gergle et al., 2004a). Such analyses permit us to understand in detail how watching others' actions affects conversation and performance. Our results show that when shared visual information is available, helpers use workers' actions in a way that is structurally similar to the way they use verbal statements when no shared visual information is available. For example, in the puzzle task, when a shared view of the workspace was available, the workers were more likely to let their actions "speak" to provide evidence of their comprehension. They were less likely to present verbal acknowledgments both when attempting to select the proper puzzle piece and when positioning a relevant piece within the workspace. The sequential analyses demonstrated that the workers' actions replaced a typical utterance when they knew that the helper could see what they were doing. Similarly, the helpers were more likely to use the workers' actions as evidence of their understanding by simply following the actions with their next description. By using actions as evidence of others' minds, pairs were able to communicate more efficiently.

CONCLUSION AND FUTURE DIRECTIONS

Surgical teams, laboratory partners, and other collaborators on physical tasks must maintain awareness of the state of the task, the status of task objects, and their partners' activities. In addition, they must maintain up-to-date mental representations of their partners' states of mind and current level of understanding. Doing so enables them to make successful inferences about the information needed at any point in time and to ground their messages more efficiently.

One particularly compelling source of evidence about others' minds is visual information. In our work, we demonstrate that helpers use visual cues to infer workers' mind states, workers' general abilities, and the state of the task. Workers, in turn, make inferences about what helpers know based on what they can see. These inferences shape their decisions about how much feedback to provide about their mind states, general abilities, and task status. Both visual information and speech serve as signals of another's state of mind and provide evidence regarding their current level of understanding. This evidence allows the pairs to ground their messages efficiently.

While visual information can signal another's level of understanding, its availability is often affected by the communication media used, which can lead to less efficient communication. While this may be a drawback to everyday communication, it is beneficial from a scientific point of view in that it allows us to understand—at a deeper level—the details of how visual information serves the purpose of successful communication via the modeling of another's state of mind. Our work in this chapter discussed an experimental approach to understanding exactly how the features of the media and task performance interact.

In our current research, we are expanding our model of how visual information is used to infer others' minds in several directions. First, we are examining how properties of joint activities such as the number of participants, sizes and types of objects, and task complexity affect the use of visual information to make inferences about others' minds. Our studies suggest, for example, that visual cues are more important in situations in which objects are difficult to name (Gergle et al., 2004b). The value of specific types of visual information such as views of others' faces or actions is also likely to be task-dependent. Whereas viewing partners' faces was relatively unimportant in the types of tasks we studied, monitoring facial expressions may be much more important for negotiation and other tasks in which assessing others' emotions is essential. Finally, we are examining how cultural differences in reliance on visual cues impacts conversational grounding across different media (e.g., Setlock, Fussell, & Neuwirth, 2004). Our overall goal is to develop a comprehensive model of the role of visual information in assessing others' minds that delineates precisely what visual cues are used, under which task, cultural, and media conditions, to infer specific attributes about others' minds.

In conclusion, visual information provides multiple resources for inferring others' minds during collaborations on physical tasks. Although some of our findings might be attributed to simpler mechanisms, such as mere behavior reading, we believe that such accounts cannot explain the full range of results. In particular, because the worker's field of view is constant across all the media conditions we examined, any differences in workers' behavior must be attributed to their beliefs about what their partners could or could not see. These findings provide strong evidence that theories of others' minds play a crucial role in collaborative tasks.

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Other Minds

How Humans Bridge the Divide between Self and Others

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