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## An Empirical Analysis of Team Coordination Behaviors and Action Planning With Application to Human–Robot Teaming


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SPECIAL ISSUE

# An Empirical Analysis of Team Coordination Behaviors and Action Planning With Application to Human-Robot Teaming

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**Objective:** We conducted an empirical analysis of human teamwork to investigate the ways teammates incorporate coordination behaviors, including verbal and nonverbal cues, into their action planning. **Background:** In space, military, aviation, and medical industries, teams of people effectively coordinate to perform complex tasks under stress induced by uncertainty, ambiguity, and time pressure. As robots increasingly are introduced into these domains, we seek to understand effective human-team coordination to inform natural and effective human-robot coordination. **Method:** We conducted teamwork experiments in which teams of two people performed a complex task, involving ordering, timing, and resource constraints. Half the teams performed under time pressure, and half performed without time pressure. We cataloged the coordination behaviors used by each team and analyzed the speed of response and specificity of each coordination behavior. **Results:** Analysis shows that teammates respond to explicit cues, including commands meant to control actions, more quickly than implicit cues, which include short verbal and gestural attention getters and status updates. Analysis also shows that nearly all explicit cues and implicit gestural cues were used to refer to one specific action, whereas approximately half of implicit cues did not often refer to one specific action. **Conclusion:** These results provide insight into how human teams use coordination behaviors in their action planning. For example, implicit cues seem to offer the teammate flexibility on when to perform the indicated action, whereas explicit cues seem to demand immediate response. **Application:** We discuss how these findings inform the design of more natural and fluid human-robot teaming.

## INTRODUCTION

In space, military, aviation, and medical industries, teams of people effectively coordinate to accomplish complex tasks that involve ordering, timing, and resource constraints. These tasks are often performed under stress induced by uncertainty, ambiguity, and time pressure. As robots increasingly are introduced into these domains (Bluethmann et al., 2003; Treat, Amory, Downey, & Taliaferro, 2005), the research community is beginning to investigate ways for mixed human-robot teams to efficiently and naturally coordinate to accomplish tasks in shared, physical workspaces (Berlin, Gray, Thomaz, & Breazeal, 2006; Breazeal, 2002; Fong, Kunz, Hiatt, & Bugajska, 2006; Hoffman & Breazeal, 2007; Lockerd & Breazeal, 2004; Sidner, Lee, Kidd, Lesh, & Rich, 2005; Trafton et al., 2005).

This article investigates how human teammates interpret and incorporate coordination behaviors into their action planning. We envision that insights from this work will be applied to inform the design of robots that effectively interpret and act in response to humans' cues and effectively generate cues to guide the humans' actions. Prior studies in human-robot interaction (HRI) indicate that implicit communications, including nonverbal cues, such as gaze direction, support efficient and robust teamwork (Berlin et al., 2006; Breazeal, Kidd, Thomaz,

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Hoffman, & Berlin, 2005; Lockerd et al., 2004). The human factors community has also identified and cataloged human coordination behaviors that promote effective teamwork by reducing communication and coordination overhead.

We have conducted an empirical analysis of team coordination behaviors to ask the next question: How do human teammates use these coordination behaviors, including verbal and nonverbal cues, in their action planning? Ultimately, these findings shall inform the design of robot task planning and execution systems that will make human-robot teaming more natural and fluid, as inspired by human-human teaming.

First, we present a short review of literature that applies insights from human-human interaction (HHI) to guide research in HRI. Next, we review a body of HHI research that has not yet been applied to HRI: studies in human teams working under stress induced by uncertainty, ambiguity, and time pressure. We then propose a new potential explanation for previous human teamwork findings and support this explanation with an empirical analysis of human teamwork experiments we carried out to investigate the use of coordination behaviors in action planning. Finally, we discuss how these findings inform the design of more natural and fluid human-robot teaming.

## Motivation: HHI as a Guide for HRI

Although the HRI community has not yet developed a consensus on theories or models for designing human-robot interfaces, the community has followed the general approach of applying HHI principles to the design of HRI in an effort to make teamwork with robots more natural and intuitive for people.

A number of HRI systems investigate the use of expression, gesture, and gaze to infer intention and maintain common understanding as the task proceeds (Lockerd et al., 2004; Sakita, Ogawara, Murakami, Kawamura, & Ikeuchi, 2004; Sidner et al., 2005). For example, in the work of Lockerd et al. (2004), robot eye gaze is used to establish joint attention, and nods are used to cement mutual understanding. In the work of Sakita et al. (2004), human gaze information is used to interpret intent, such as hesitation or search for an object. These systems are well informed by human studies. Empirical evidence suggests that expression and gesture are powerful forms of communication. For example, Lozano & Tversky (2006) found that humans understood and learned from gesture-only instructions better than from speech-only instructions.

Other systems for human-robot teamwork address the challenge of coordinating actions and task assignments primarily through the use of explicit verbal exchange of information. In the work of Trafton et al. (2005), a person verbally commands a robot capable of reasoning about the world from the perspective of the human teammate. The robot effectively acts in response to a person issuing commands using various frames of reference (egocentric, object centered, exocentric, etc.). Another system, the Human-Robot Interaction Operating System (HRI/OS; Fong et al., 2006) accomplishes collaboration through a central task manager, which decomposes goals into high-level tasks, and assigns tasks to either the human or the robot. Coordination is accomplished through verbal exchange of information regarding goals, abilities, plans, and achievements.

More recently, robotic systems have been designed to coordinate teaming behavior more fluently through practice by learning a model of the spatial-temporal performance of the person (Hoffman & Breazeal, 2007). Other efforts have included robots designed to infer mental states to coordinate joint action, such as beliefs and intents, by observing nonverbal human behavior (Breazeal, Gray, & Berlin, 2009).

There is interest in designing systems for human-robot teamwork based on observations from human studies. For example, the work of Trafton et al. (2005) is grounded and motivated by studies of astronaut-to-astronaut interactions. However, many of the current systems for higher-level human-robot coordination rely on explicit commands between the human and the robot or on a central agent that explicitly commands the actions of both the human and the robot. Studies in human teamwork suggest that these are not efficient strategies for team coordination. Instead, high-performing teams of people make use of implicit coordination strategies, including verbal and nonverbal cues, to reduce communication and coordination overhead.

This article lays the foundation for translating research in human teamwork to enable effective human–robot teamwork. We conduct an empirical analysis of human teamwork that goes beyond previous studies investigating what coordination behaviors people use by investigating how teammates use and respond to various types of coordination behaviors. We intend for our work to inform the design of robots that effectively interpret and act in response to humans' cues and that effectively generate cues to guide humans' actions. We also encourage experimentation to investigate whether the use of effective human–human coordination behaviors improves human–robot team performance.

## Strategies to Reduce Communication and Coordination Overhead

Serfaty, Entin, and Deckert (1993) conducted experiments indicating that human teams alter coordination strategies as uncertainty or time pressure increases. Serfaty et al. experimented with a task in which a team collaborated and shared information to identify targets. Serfaty et al. found that increasing uncertainty associated with target identity did not affect the error rate of the team. Also, teams were able to maintain the same performance outcome with only one third of the original time available for the task. It appeared during these experiments that teams were changing their coordination and information-seeking strategies.

In general, teams are able to maintain or improve their performance under stress by switching from explicit to implicit coordination behaviors (Orasanu, 1990; Salas, Fowlkes, Stout, Milanovich, & Prince, 1999; Stout, Cannon-Bowers, & Salas, 1996). Explicit coordination behaviors include communications meant to control teammates actions and prompts or requests for information. Implicit coordination behaviors include implicit communications and strategies that reduce communication and coordination overhead (Entin & Serfaty, 1999). Implicit communications preempt the actions and needs of others by providing information to indirectly guide teammates' actions and are offered without explicit request (Entin & Serfaty, 1999; Entin, Serfaty, & Deckert, 1994; Orasanu, 1990; Serfaty et al., 1993; Volpe, Cannon-Bowers, Salas, & Spector, 1996). For example, periodic situation assessment has been shown to be an effective implicit communication strategy (Entin & Serfaty, 1999; Mackenzie, Xiao, & Horst, 2004). Orasanu (1990) found that effective aircrews included copilots who increased the amount of unsolicited information and captains who decreased the number of requests for information during high-workload periods.

Other implicit coordination strategies include preplanning, efficiently using idle periods (Entin et al., 1994), and dynamically redistributing workload among team members (Entin et al., 1994). For example, planning prior to the task, during low-workload periods while performing the task, or both can enhance team effectiveness (Orasanu, 1990; Stout, Cannon-Bowers, Salas, & Milanovich, 1999). Human resource literature (summarized in Stevens & Campion, 1994) suggests that as task complexity increases to involve more interdependence among team members (through ordering, timing, or resource constraints), the impact of coordination on team output also increases (Cheng, 1983).

## Shared Mental Models (SMMs)

Empirical evidence indicates that implicit coordination strategies are promoted by the use of SMMs among team members (Blickensderfer, Cannon-Bowers, & Salas, 1997; Volpe et al., 1996). SMMs provide team members "with a common understanding of who is responsible for what task and what the information requirements are. In turn, this allows them to anticipate one another's needs" so that team members can coordinate effectively (Stout et al., 1999). For example, Blickensderfer, Cannon-Bowers, and Salas (1997) found that teams that shared expectations regarding member roles and task strategies before a radar tracking task communicated more efficiently during the task and achieved higher overall performance outcomes. Also, Volpe et al. (1996) found improved team performance outcomes when team members had been "cross-trained" to learn the tasks, responsibilities, and informational needs of other teammates.

Studies of cognitive and neural processes involved in joint action (Sebanz, Bekkering, & Knoblich, 2006) also underscore the importance of SMMs. For example, evidence suggests that people incorporate the resources and capabilities of other team members into their own action planning. Also, studies of anticipatory action control indicate that shared representations of tasks allow individuals to "extend the temporal horizon of their action planning, acting in anticipation of others' actions rather than simply responding" (Sebanz et al., 2006, p. 73).

The research community has made progress in developing measures of team shared cognition and the quality of SMMs. For example, Cooke, Salas, Cannon-Bowers, and Stout (2000) have applied techniques to measure teammates' task- and team-related knowledge both during missions and after, or in between, missions. Also, Langan-Fox, Code, and Langfield-Smith (2000) review methods for eliciting, representing, and analyzing SMMs. The review summarizes the advantages and disadvantages of each method and provides recommendations regarding when to use each method.

### Enhancement of Team Performance Through Planning and Training

A great deal of research effort has focused on how to enhance SMMs and foster implicit coordination for improved team performance. Planning is one way of developing and enhancing SMMs (Stout et al., 1996). Nine planning dimensions are identified as important (summarized in Stout et al., 1999): (a) creating an open environment, (b) setting goals and awareness of consequences and errors, (c) exchanging preferences and expectations, (d) clarifying roles and information to be traded, (e) clarifying sequencing and timing, (f) discussing handling of unexpected events, (g) discussing how high workload affects performance, (h) pre-preparing information, and (i) self-correcting.

Stout et al. (1999) and Orasanu (1990) found that more effective teams engaged in more types of planning behaviors than did less effective teams. Also, teams that engaged in more types of planning behaviors used more efficient communication strategies during high-workload periods (Stout et al., 1999). Studies have also shown team training methods to be successful in promoting team performance. For example, Volpe et al. (1996) and Salas et al. (1999), respectively, found cross-training and crew resource management training to enhance team performance outcomes.

## HYPOTHESES

One of the most interesting findings of these teamwork studies is that team performance improves with increased use of implicit communications (Orasanu, 1990; Stout et al., 1999). In other words, explicitly commanding a teammate to perform an action seems to be less efficient on average than providing relevant information to indirectly guide the teammate's actions. We propose a new theoretical explanation for this result and offer the first support for this explanation with a set of experiments we carried out to investigate the use of coordination behaviors in action planning.

### "Switching Costs" as an Explanation for Benefits of Implicit Communication

We hypothesize that explicit communications, which command specific actions, necessitate an immediate response from the team member. We suggest that a team member's tendency to immediately respond to the specific commanded action would degrade team performance in two ways. First, responding to the command may involve a "switching cost," meaning that extra time is required for the recipient of the command to stop what he or she is doing, switch his or her attention to address the command, and then switch attention back to resume his or her work. The temporal cost of switching between simple tasks is well documented (Rogers & Monsell, 1995; Yeung & Monsell, 2003).

Second, the cost of task switching is magnified in dynamic domains with complex ordering, timing, and resource constraints. In multiagent planning and scheduling problems, one often sees that small changes in the task assignment, scheduling, or ordering of activities can significantly affect plan quality (Estlin, Gaines, Fisher & Castano, 2005; Mehler & Edelkamp, 2004; Pecora & Cesta, 2005). We suggest that the reflex to immediately respond to a command does not allow flexibility to efficiently incorporate the commanded action into the workflow, thereby degrading human team performance.

In contrast, we hypothesize that implicit communications, meant to indirectly guide the teammate's actions, do not necessarily refer to specific actions and do not necessitate an immediate response. We suggest that this ambiguity in what to do and flexibility in when to act would allow teammates to incorporate actions more efficiently into their workflow. Also, there is some evidence that an extended response window attenuates the time cost of switching between simple tasks (Rogers & Monsell, 1995).

In this article, we provide the first support for a switching-cost explanation for the benefits of implicit communication. We investigate three hypotheses addressing the use of coordination behaviors in action planning and provide empirical evidence that people use and respond to implicit communications differently than to explicit communications. We leave the quantitative investigation and modeling of the switching cost to future work. Nonetheless, our empirical findings have potentially important applications to the design of effective and natural human-robot teaming (see Application to Human-Robot Teaming).

*Hypothesis 0 (validation of previous studies):* We aim to replicate results from previous studies demonstrating that teams exhibit increased use of implicit coordination behaviors as time pressure increases (Entin & Serfaty, 1999; Serfaty et al., 1993) and that increased use of implicit coordination behaviors is positively correlated with improved team performance outcomes (Orasanu, 1990; Stout et al., 1999).

*Hypothesis 1:* We expect teammates to exhibit varying speeds of response to communications depending on communication type, including implicit, explicit, verbal, and nonverbal cues. Specifically, we expect that nearly all explicit communications will elicit an immediate response. We also expect that implicit communications (including verbal and nonverbal cues) will elicit a flexible-time response more often than will explicit communications.

*Hypothesis 2:* We expect the specificity of communications, measured by the number of possible actions to which each implicit, explicit, verbal, or nonverbal cue may refer, to be dependent on communication type. Specifically, we expect that nearly all explicit communications will refer to one specific action. We also expect implicit communications to refer to one specific action less often than explicit communications.

## METHOD

### Participants

The participants consisted of 60 people (31 men and 29 women) recruited from the Massachusetts Institute of Technology and Greater Boston area. The average age was 25.0 years (*SD* = 8.4). The participants were organized into randomly selected teams of 2. Each participant was compensated with a $10 gift certificate.

### Experimental Task

We developed a synthetic task to recreate aspects of tasks performed by teams in space, military, and medical domains. A synthetic task is a "research task constructed by systematic abstraction from a corresponding real-world task" (Martin, Lyon, & Schreiber, 1998). We developed the synthetic task by abstracting features from two real-world tasks: (a) two astronauts working together on an extravehicular activity and (b) a surgical technician and surgeon working together in the operating room. Key features of these real-world tasks include (a) tightly coupled "hand-to-hand, face-to-face" interaction, (b) physical actions with (partial) ordering and resource constraints, and (c) a sense of time pressure.

This study concerns investigating the ways human teammates use coordination behaviors in action planning when performing tasks with these three features. Thus, the synthetic task must capture these features but may not have the "look and feel" of the described operational environments (Cooke & Shope, 2005). To this end, we created an experimental task in which teams of two people built predefined structures (presented in Figure 1) using an off-the-shelf building block set.

The composition of the structures was chosen to impose interdependence among team members through ordering and resource constraints in the following way. One member of the team was permitted to manipulate only tan blocks. Each tan block is labeled with a *t* in Figure 1.

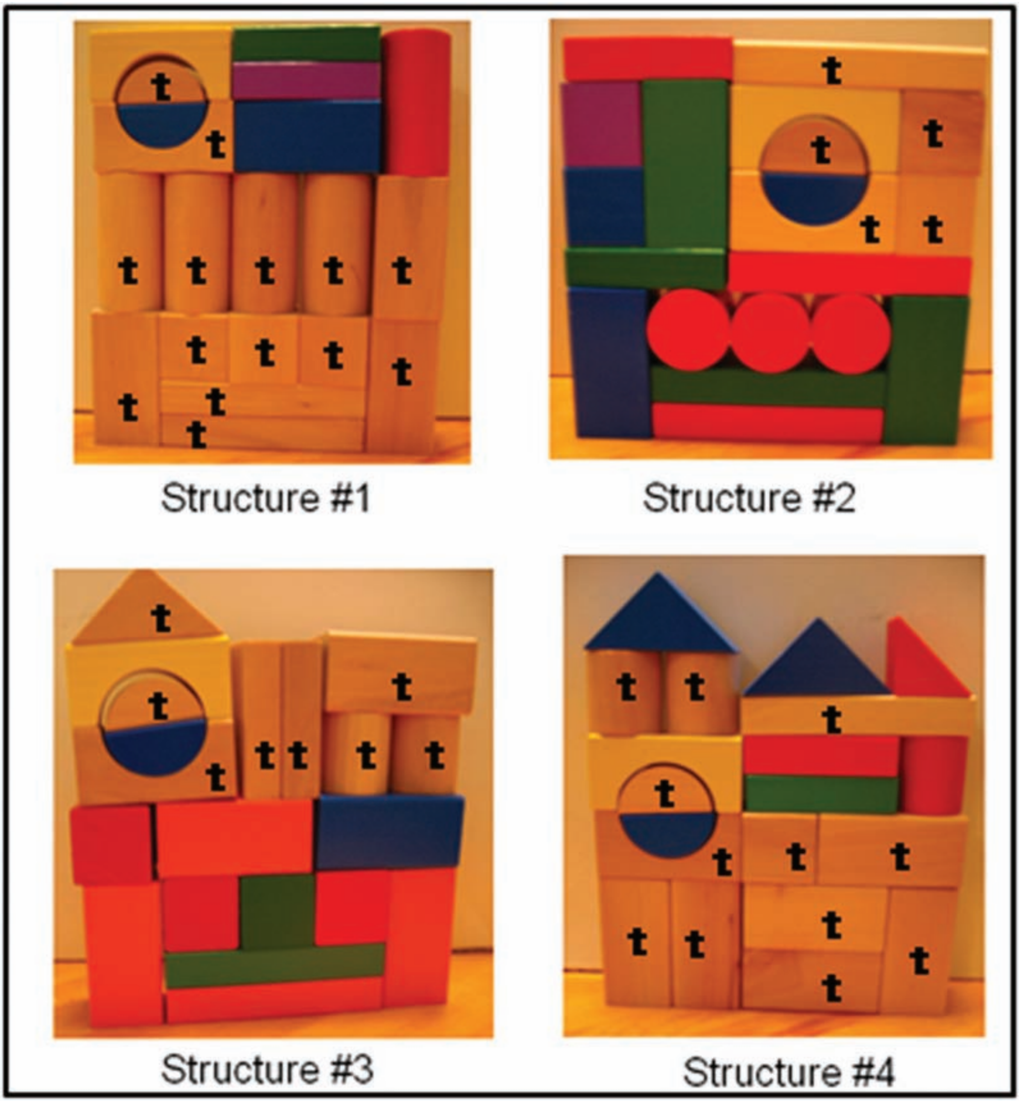


*Figure 1.* Four structures used in experimental task.

The other member of the team was permitted to manipulate only colored blocks. This resource constraint resulted in natural ordering constraints as the team built structures from the bottom up. Additional constraints were imposed by providing the teams with too few blocks to build all four structures simultaneously. The team member manipulating tan blocks was provided with only four tan cubes and therefore could not complete Structures 1 and 2 at the same time. The team member manipulating the colored blocks was provided with only two short, thin rectangular prisms and therefore could not complete Structures 1 and 2, Structures 1 and 4, or Structures 2 and 4 at the same time. These constraints magnified the importance of tightly coupled coordination to build and dismantle structures. Without effective coordination, one team member would be forced to sit idle and degrade the team's performance outcome (measured as time to complete building all four structures). Each structure was also designed with relatively large sections of either tan or colored blocks, providing teammates with the opportunity to dynamically adjust to low-workload periods (i.e., prepare to build another structure).

## Independent Variable

Thirty teams of two people performed the experimental task. Fifteen teams were randomly chosen to perform the task under time pressure (stress group). The other 15 teams, the control group, performed the task without time pressure. Manipulating this independent variable allowed us to compare the use of coordination behaviors in teams performing under time pressure with that in teams performing without time pressure. This manipulation also allowed us to investigate whether the use of communications in action planning was dependent on the context in which the communication is used (with or without time pressure).

A competitive environment was fostered in the stress group to induce a sense of time pressure. These teams were told their goal was to build the four structures as quickly as possible and were given the benchmark "best completion time to date." Best completion time to date was based on the pilot study performance outcomes and was calculated as approximately 20% faster than the best completion time recorded in the pilot study. The stress group was also provided with a prominently displayed timer to provide continuous feedback of their progress in relation to the benchmark. In contrast, control group teams were told that they had as long as they wanted to complete the task and were not provided with the benchmark best completion time to date or with a timer.

## Dependent Measures

Each coordination behavior exhibited by stress group and control group teams was classified according to the matrices presented in Tables 1 and 2 as (a) implicit or explicit and (b) verbal, nonverbal, or combined (meaning both verbal and nonverbal together). Coordination behaviors were identified in the audio and video recordings of the experiment and were classified separately by two analysts, the primary author and an independent analyst. Agreement between the two analysts was found to be high for all measures. Coefficient alphas were .79 or higher (Cronbach, 1970).

Two dependent measures were collected for each coded coordination behavior through analysis of audio and video recordings of the experiment. First, the speed of response to each explicit and implicit communication was measured. Second, the specificity of each communication was measured.

*Classification of explicit communication.* The analysts classified each explicit communication exhibited by each team performing the experimental task. Analysts used a specifically designed matrix to code explicit communications. This matrix is presented in Table 1 and includes an example of each type of explicit communication. Explicit communications include (a) commands meant to control the teammates' future actions and (b) prompts or requests for information. A command was classified as explicit if it included two out of the following three pieces of information: what action to perform (i.e., "put"), what is to be manipulated (i.e., "the red block"), and where within the workspace the action is to be performed (i.e., "on Structure 2"). For our experimental task, we categorized prompts or requests for information according to their subject, regarding subtasks completed, subtasks started, or subtasks in progress. Each explicit communication was further categorized by its mode of communication: verbal only, nonverbal only (gesture), or combined.

*Classification of implicit communications and use of idle time.* The analysts cataloged each implicit communication exhibited by each team while performing the structure-building task. Analysts used a specifically designed matrix to code implicit communications. This matrix is presented in Table 2 and includes an example of each type of implicit communication. Implicit communications include (a) anticipatory offering of information to a teammate and (b) status updates and are further categorized according to subject and mode of communication. Analysts also measured (c) efficient use of idle time. They assessed efficient use of idle time by recording each team's cumulative idle time while it performed the experimental task. Teams with lower cumulative idle time used low-workload periods more efficiently. We defined idle time of a teammate as the cumulative amount of time the teammate spent watching the actions of the other while not holding a building block.

*Speed of response to communications.* Analysts recorded the speed of response for each explicit and implicit communication. The speed of response to each communication was coded as either immediate or not immediate, depending on the number of actions Teammate B executed

**TABLE 1:** Matrix Used to Code Explicit Coordination Behaviors

| Explicit Coordination Behavior | Mode of Communication: Verbal Only | Nonverbal (Gesture) Only | Verbal + Nonverbal |
|---|---|---|---|
| Attempts to control teammates' actions | | | |
| Explicit command for future action (what to do, with what, where) | "Place the square block on top of Structure 4" | N/A | "Put the arch block here" + finger point |
| Prompts or requests for information | | | |
| Subtasks completed | "Is structure 1 complete?" | N/A | "Is this one done?" + finger point |
| Subtasks started | "What structure are you starting? | N/A | "Which one is that?" + finger point |
| Subtasks in progress | "What are you working on?" | N/A | "Is this Structure 2?" + finger point |

*Note.* N/A = not applicable.

**TABLE 2:** Matrix Used to Code Implicit Coordination Behaviors

| Implicit Coordination Behavior | Mode of Communication: Verbal Only | Nonverbal (Gesture) Only | Verbal + Nonverbal |
|---|---|---|---|
| Anticipatory offering of info to teammate | | | |
| Cue future action with implicit attention getter | "Here"; "This one"; "Number 3" | Finger point | "Here" + finger point |
| Offer info on possible actions | "Structure 2 ready for you" | N/A | "This is ready for your blocks" + finger point |
| Status updates | | | |
| Subtasks completed | "Structure 1 complete" | N/A | "This one is done" + finger point |
| Subtasks started | "I'm starting Number 4" | N/A | "I'm starting 4 here" + finger point |
| Subtasks in progress | "I'm working on Structure 2" | N/A | "This is Structure 2 in progress" + finger point |
| Efficient use of idle time[a] | | | |
| Dynamic redistribution of workload | N/A; person/agent can efficiently use idle time without communication with team member | | |
| Preplanning | | | |

*Note.* N/A = not applicable.
*a.* Efficient use of idle time may be facilitated by other implicit and explicit coordination behaviors.

before responding to Teammate A's communication. If Teammate B responded immediately to the communication with the next action, then the response was coded as immediate. If Teammate B took more than one action to respond to the communication, then the response was coded as not immediate.

*Specificity of communications.* Analysts also recorded the specificity of each explicit and implicit communication. The specificity of each communication was coded as either specific or nonspecific, depending on the number of actions that the communication may have possibly referred to. Analysts coded specificity taking into consideration the current state of the task and any verbal and nonverbal cues. For example, if Teammate A exhibited a finger point toward Structure 4, the analysts coded specificity by considering all possible next actions that Teammate B could perform on Structure 4.

### Procedure

The experiment was divided into two parts: a familiarization phase and test phase. After arrival, team members were seated at a table across from one another. The table surface in between the teammates provided the shared workspace used to manipulate the building blocks during both the familiarization and the test phases. Prior to the familiarization phase, the team was provided access to the building blocks. Each team member was provided pictures of the four structures to be built during the test phase. The team was also read a description of the experimental task, including an assignment of which team member would manipulate tan blocks and which would manipulate color blocks.

During the familiarization phase, teams were provided access to the building blocks and pictures of the four structures to be built during the test phase. The team members were permitted to talk, strategize, organize their blocks, and practice building structures. The familiarization phase lasted for 15 min or ended when the team members decided together to terminate the familiarization phase early.

Participants were provided instructions for the test phase after the familiarization phase ended. Teams were instructed that the test phase would consist of three trials. In each trial, the team must build all four structures. Team members were instructed that while performing the trials, (a) the order in which they built the structures was up to them; (b) they may build more than one structure at a time; and (c) after a structure was completed, they would get credit for building it and the structure did not have to remain intact while they built other structures. Teams were also instructed to manipulate one block in each hand at a time during the trials. Between trials, the team would be provided up to 5 min to dismantle any structures and organize their workspace in preparation for the next trial. Also, between trials, the team members would be permitted to talk, strategize, and practice building structures. However, teams would not be permitted to prebuild structures before the trials.

A competitive environment was fostered with the stress group to induce a sense of time pressure, as described previously. In contrast, control group teams performed the task without time pressure. Teams were not told that they lacked enough blocks to build all four structures at the same time. Teams were expected to uncover this information as they built an SMM of the task during familiarizing or during their first trial.

## RESULTS

Previous studies demonstrated that teams exhibit increased use of implicit coordination behaviors as time pressure increases (Entin & Serfaty, 1999; Serfaty et al., 1993). Also, studies have shown that increased use of implicit coordination behaviors is positively correlated with improved team performance outcomes (Orasanu, 1990; Stout et al., 1999). We report findings consistent with the results of these previous studies. We also test two hypotheses related to action planning and not addressed in previous studies. We investigate (a) the speed of response and (b) specificity to different types of communications.

## HYPOTHESIS 0: VALIDATION OF PREVIOUS STUDIES

Results from the human teamwork experiments validate previous findings that teams exhibit increased use of implicit coordination behaviors as time pressure increases. We analyzed the third trial in comparing the stress and control groups to minimize the effect of differences in planning during the familiarization phase. Stress group teams used an average of ~69% more implicit communications than control group teams. Control group teams exhibited on average 4.5

(±0.1) implicit communications in the third trial, whereas stress group teams exhibited on average 7.6 (±0.1). A two-tailed, unpaired *t* test with unequal variance found this difference to be a statistically significant difference ($df = 28$, alpha = .5, $t = 3.64$, $p < .05$).

In particular, decreased idle time (i.e., more efficient use of low-workload periods) was very strongly correlated with improved team effectiveness in both the stress and control group teams ($r = .92 \pm .03$ and $r = .90 \pm .04$, respectively). Stress group teams spent on average 33 s idle (*SD* = 31 s) and took on average 146 s to complete the task (*SD* = 64 s). Control group teams spend on average 101 s idle (*SD* = 84 s) and took on average 240 s to complete the task (*SD* = 89 s).

Our results also validate previous findings that an increase in the use of implicit communications is correlated with improved team effectiveness. We investigated the correlation between the percentage of implicit communications (number implicit ÷ total number of communications in the trial) and team effectiveness. In this study, we used time to completion as the measure of team effectiveness. Faster time to completion indicates increased team effectiveness. In stress group teams, the correlation between use of implicit communications and improved team effectiveness was strong ($r = .78 \pm .06$). In control group teams, the correlation was less strong ($r = .44 \pm .04$). The error measures in the reported statistics indicate the impact of discrepancies in the two analysts' classifications.

### Hypothesis 1: Speed of Response

Analysis shows that 80% of implicit communications were responded to immediately with the next action. In contrast, 99% of explicit communications were responded to immediately. This difference is statistically significant ($\chi^2 = 15.95$, $df = 4$, $p < .005$). There was no statistical difference in response between the stress and control groups (comparison of implicit behaviors, $\chi^2 = 0.02$, $df = 4$, $p > .05$; comparison of explicit behaviors, $\chi^2 = 0.03$, $df = 4$, $p > .05$), and no statistical difference for different modes of communication: verbal, nonverbal, or combined (ranges for pairwise comparisons, $\chi^2 = 0.02–2.68$, $df = 4$, $p > .05$). See Table 3 for coordination behavior frequency data.

**TABLE 3:** Frequency Table of Coordination Behaviors

| Type of Coordination Behavior | Stress Group | Control Group |
|---|---|---|
| Implicit nonverbal only | 18 | 8 |
| Implicit verbal only | 71 | 17 |
| Implicit combined | 65 | 13 |
| Explicit verbal only | 11 commands | 8 commands |
| Explicit combined | 53 commands | 23 commands |

### Hypothesis 2: Specificity

Analysis shows that 53% of verbal and combined communications were specific, whereas 100% of nonverbal-only implicit behaviors were specific. Furthermore, 90% of verbal and combined explicit communications were specific. These differences were statistically significant (ranges for pairwise comparisons, $\chi^2 = 4.37–54.58$, $df = 4$, $p < .05$), and there was no statistical difference between stress and control groups (ranges for pairwise comparisons, $\chi^2 = 1.29–2.11$, $df = 4$, $p > .05$). See Table 3 for coordination behavior frequency data.

## DISCUSSION

The results of our experiments provide valuable insight into the ways humans incorporate explicit and implicit communications into their action planning and provide the first support for a switching-cost explanation for the benefits of implicit communication. We confirmed the hypothesis that the ways in which humans incorporate communications into their action planning are a function of whether the communication is implicit or explicit. Additionally, we found that the ways in which teams interpreted and incorporated both implicit and explicit communications into their action planning remained the same (for the dimensions analyzed) regardless of whether the task was performed under time pressure.

Specifically, we found that implicit verbal and combined cues did not often refer to one specific action and seemed to offer the teammate flexibility on when to respond to the cue. In contrast, explicit verbal and combined cues were used to refer to one specific action and seemed to demand immediate response from the teammate. Interestingly, implicit nonverbal cues (gestures) were found to be unique in that they were used to refer to one specific action yet seemed to offer the teammate flexibility on when to respond to the cue. This last result is particularly intriguing, because it suggests that gesture may be used to direct a specific action potentially without incurring the full switching cost associated with explicit commands. Although this last finding is statistically significant, it is based on only 26 coded gestures and merits further investigation.

### Application to Human-Robot Teaming

Our findings lay the foundation for translating research in human teamwork to enable effective human-robot teamwork. In this study, we have investigated how human teammates incorporate explicit and implicit communications into their action planning. Ultimately, we envision that insights from our study will inform the design of robot task planning and execution systems that will make human-robot teaming more fluid and natural, like human-human teaming.

Following the general approach of applying HHI principles to HRI, we hypothesized that an effective robot teammate should (a) react to the human's communications in ways that seem natural to the human and (b) communicate with an understanding of how the human teammate will incorporate the cues into his or her action planning. On the basis of insights from our experiments, we propose that a robot should respond to communications differently, depending on whether they are implicit, explicit, verbal only, nonverbal only (gesture), or combined. For example, a robot should respond immediately to explicit verbal and combined verbal and nonverbal cues. Also, a robot should not necessarily respond immediately to implicit verbal, nonverbal, and combined cues. Instead, the robot may take advantage of the implied flexible response time to reason about the optimal time to respond to the cue.

On the basis of insights from our experiments, we propose that a robot should exhibit different types coordination cues with an understanding of how the teammate will incorporate the cues into his or her action planning. For example, we propose that a robot should use explicit cues to refer to one specific action and/or in situations that demand immediate response from the teammate. Also, when possible, the robot should promote efficient coordination by using implicit cues that offer the teammate flexibility on when to respond. For example, the robot may use implicit cues to preempt the needs of the teammate by directing the teammate's attention toward unfinished work or a problem.

Interestingly, we found that the ways teammates use and incorporate coordination behaviors into their action planning are the same (for the dimensions analyzed), regardless of whether they are motivated to coordinate efficiently. We believe this finding has important implications for human-robot teaming. We hypothesize that a robot reacting to and exhibiting coordination behaviors, on the basis of insights from this study, will seem "natural" to the human teammate regardless of whether the teammates are performing a task under time pressure.

We have provided a starting point for translating research in human team coordination to enable effective human-robot teamwork. We encourage human-robot experimentation to investigate these hypotheses and to test the validity of applying insights from human team studies to achieve efficient and natural human-robot teaming.

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