How Real-Time Signaling Improves Ad Hoc Collaboration

Xinyue Hu
xhu26@uci.edu
University of California, Irvine

Zahra Zahedi
zahra_zahedi@honda-ri.com
Honda Research Institute USA

Kumar Akash
kakash@honda-ri.com
Honda Research Institute USA

Mark Steyvers
mark.steyvers@uci.edu
University of California, Irvine

Abstract

Many collaborative tasks require people to coordinate interdependent actions under time constraints, often without explicit communication. In such ad hoc settings, observing others' emerging intentions may help groups rapidly align their actions. While information cascades are often studied as sources of bias in individual decision-making, they may play a constructive role in coordination by facilitating fast convergence on shared plans. We investigated this possibility in a multi-agent coordination task in which teams of three repeatedly solved a time-constrained block-moving problem (N = 471). We manipulated whether players could observe others' intentions in real time or only observe the outcome of each round. Teams with real-time signaling were more likely to complete the task. Within rounds, early votes were frequently followed by teammates, and these actions typically advanced task progress along efficient paths. Together, these findings suggest that access to real-time intention signals supports efficient ad hoc coordination by reducing decision uncertainty and stabilizing shared action plans.

Keywords: ad hoc collaboration, coordination, real-time signaling, joint action, collective behavior

Introduction

In everyday life, people often need to coordinate their actions with others under uncertainty and time pressure. Successful joint action requires not only accurate individual decisions but also the ability to align actions with others in real time (Sebanz et al., 2006; Rhim & Goyal, 2018).

A large body of research has examined how people use the publicly observable actions of others to guide their own choices (Çelen & Kariv, 2004). A well-known example comes from Asch's line-judgment studies, where people often went along with an obviously incorrect answer, such as saying that two differently sized lines were the same length, simply because everyone before them had done so (Asch, 1956). Much of this work focuses on sequential decision-making settings in which individuals act one at a time and observe the choices of those who acted before them (Fisher & Wooders, 2020; Anderson & Holt, 1998). A key finding is that information cascades can arise when early actions exert disproportionate influence on later decisions, sometimes leading individuals to disregard their own private information and follow an emerging consensus (Anderson, 2001; Nöth & Weber, 2002; Huck & Oechssler, 2000; Nielsen et al., 2024; Alevy et al., 2007). These cascades are robust but can produce both positive and negative collective outcomes (Ziegelmeyer et al., 2010; Schöbel et al., 2016). More recent work suggests that observing others' actions can improve collective performance, particularly when individual signals are weak (Agranov et al., 2022; Toyokawa & Gaissmaier, 2022; Tump et al., 2020).

While this literature has provided important insights into how information spreads through groups, it has largely focused on relatively simple settings: binary decisions or belief reports in which individuals' actions don't directly alter the environment or constrain what others can do. Many real-world group tasks, however, require coordination over sequences of interdependent actions, where early decisions shape later options and collective success depends on aligning plans rather than simply converging on the correct belief.This raises a key question: in settings requiring coordinated action, how do cascade-like dynamics operate, and do they help or hinder group coordination?

Recent research on human coordination confirms that the real-time visibility of others' actions improves coordination outcomes in spatial games (Antonioni et al., 2014), hierarchical tasks (Schmid & Braun, 2025), and even simple dyadic interactions (Oullier et al., 2008). However, most work has not examined whether cascade-like dynamics, where early signals disproportionately influence others, emerge in these settings, nor how such dynamics interact with varying coordination demands. In belief-formation tasks, cascades can lead people to disregard private information (Anderson, 2001), but in coordination tasks with heterogeneous action requirements, early alignment might facilitate efficient group performance (Kleiman-Weiner et al., 2016).

We address two primary questions. First, does access to real-time intention signaling improve coordination efficiency, such that teams with visible information about others' intentions are more likely to complete tasks? Second, does coordination efficiency change over repeated interactions as teams learn across successive levels?

We study these dynamics using a multi-player block-moving task inspired by real-world scenarios like moving furniture together. Consider working with two others to move three boxes: should you start with the small box you can move alone, or signal cooperation by attempting a larger box that requires help? In our task, teams of three must move blocks requiring different levels of coordination (1, 2, or 3 players) to designated slots. We manipulate whether players can observe teammates' voting intentions in real time dur-

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ing decision windows or only see outcomes after votes are finalized. This allows us to investigate whether early votes attract alignment from teammates and whether such cascade-like following is adaptive in coordination contexts, particularly for actions requiring multi-player agreement.

Our results show that real-time intention visibility substantially improves coordination efficiency, and that early-vote following, particularly for actions requiring multi-player coordination, was adaptive rather than merely imitative.

Method

To study how coordination emerges under different informational conditions, we designed a simple block-moving game to examine post-hoc coordination in small groups. Participants worked in teams of three to solve a time-constrained block-moving task across multiple levels. We manipulated whether players could observe others' voting intentions in real time or only saw the outcome of each round after votes were finalized.

Game Setup

Figure 1 illustrates the game setup. The game consists of three elements—blocks, slots, and obstacles—and is played by a team of three players. The objective is to move all blocks into slots while navigating around obstacles on a grid. Each block requires between one and three players to move. Some blocks can be moved by a single player, whereas others require two or all three players to vote for the same direction before a move is executed. All blocks can be placed into any slot, and once a block is placed, it disappears, allowing the slot to be reused.

The environment also contains two types of obstacles: movable obstacles, which can be shifted one step at a time with a single vote, and fixed obstacles, which permanently block paths. Information about the map layout, block voting requirements, and whether an obstacle is movable or fixed is publicly available to all players. Figure 1 shows the four different layouts used in the game. Each layout contains one block of each type, two slots, and a varying number of obstacles.

Coordination unfolds over multiple rounds of voting and execution. During each five-second voting period, all players can cast a directional vote (up, down, left, or right) on any block or movable obstacle, and may change their vote at any time within the voting window. After the voting period ends, if the required number of players have voted for the same direction on the same item, that item moves one step. The round then ends, and the next five-second voting period begins immediately.

Teams continue making decisions across rounds until either all blocks are placed into slots or the maximum number of rounds is reached. The game is designed to allow players to adapt their planning strategies by observing and learning from others' intentions, while operating under a strict time constraint. Overall, the task implements a shared-control structure and enables observation of how group coordination dynamics develop over time.

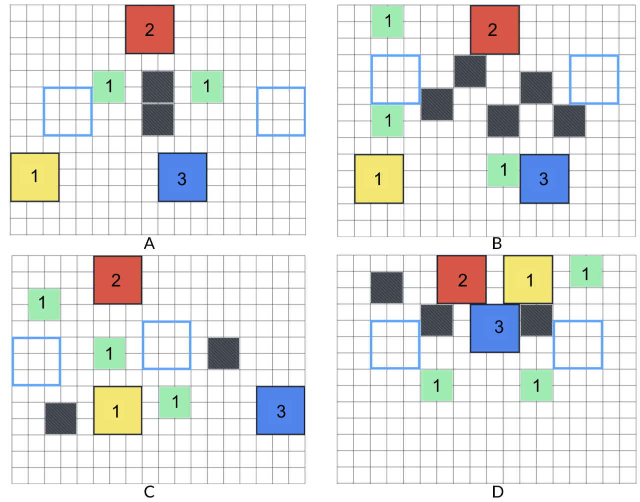
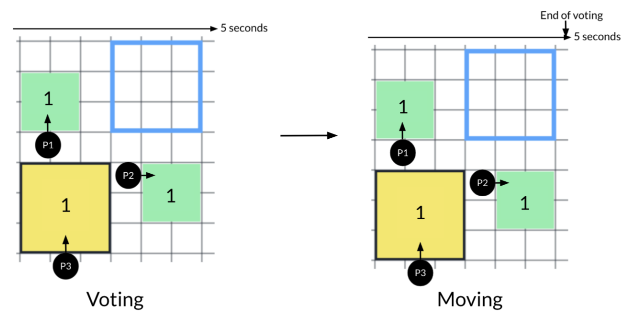


Figure 1: The four layouts employed in the block-moving game. Yellow, red, and blue blocks represent the 1, 2, and 3-person blocks respectively that need to be moved to the target slots (blue transparent squares). Green squares represent movable obstacles that can be moved by a single person. The grey squares represent immovable obstacles. Each level was designed such that the optimal centralized solver solution required 20 rounds. The user interface shown here is for illustrative purposes and does not exactly match the game environment.

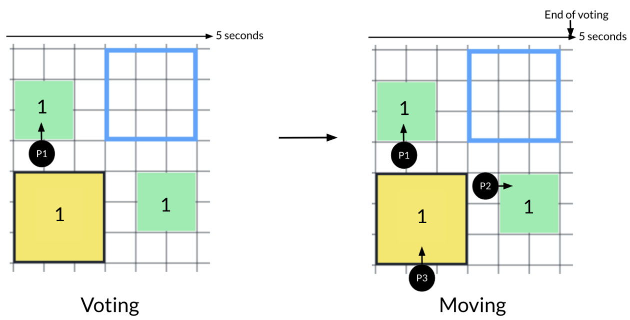
Optimal Solving algorithm

To establish a standard benchmark for optimal performance in the game, we built an optimal solver that identifies the shortest possible sequence of moves needed to complete each map layout shown in Figure 1. The solver respects all game rules, including movement constraints, voting requirements, and collision restrictions. Importantly, all layouts were designed and verified using the optimal solver to require exactly 20 rounds under optimal coordination between three players.

The solver treats the block-moving task as a fully centralized planning problem. Rather than modeling individual players or communication delays, it assumes that all three players' actions can be planned together with full information. Under this assumption, each round provides up to three action opportunities, corresponding to the combined movement capacity of the three players. The solver filters out any combinations that violate game rules, move objects out of bounds, or cause collisions. Among the remaining legal options, the solver searches for the sequence of joint actions that leads to task completion in the fewest rounds. The search is implemented using an A* algorithm that relies on a heuristic that estimates how far each block is from its nearest slot, based on a precomputed distance map. This allows the solver to prioritize promising states while still guaranteeing optimal-



(a) Real-time Signaling



(b) No Signaling

Figure 2: Illustration of the two experimental conditions. The user interface shown here is for illustrative purposes and does not exactly match the game environment. (**Top**) Real-time Signaling condition, in which players can observe others' voting intentions in real time. The left panel shows the 5-second voting interval, during which the focal player (P1) can see the votes of the other two players; the right panel shows the state after the voting interval concludes. (**Bottom**) No Signaling condition, in which players can only observe the outcome of each round after votes are executed. The left panel shows the voting interval, during which the focal player (P1) can see only their own vote; the right panel shows the state after the voting interval concludes, at which point all players' votes are visible.

ity.

Experimental Design

The study was conducted with groups of three players. Each group worked together to complete all four layouts shown in Figure 1, which we refer to as completing four levels as a team. To control for potential order effects, a Latin square design was used to vary the order in which the four layouts were presented across teams. This resulted in four between-subjects conditions, each corresponding to a different sequence of levels.

In addition to layout order, we manipulated the availability of social information through signaling conditions. In the real-time signaling condition, players could observe others' voting intentions during each voting period in real-time (Figure 2a). This allowed players to adjust their actions in response to others' intentions within a round. In contrast, in the no-signaling condition, players did not have access to real-time intention information and could only observe the outcome of each round after votes were executed (Figure 2b).

Crossing layout order with signaling availability resulted in a total of eight experimental conditions. Data for the real-time signaling conditions were collected first and included 117 sessions (351 participants total). A larger number of sessions was collected for this condition to support analyses of coordination dynamics and performance. The no-signaling condition was collected subsequently and included 40 sessions (120 participants total). This condition served primarily as a performance baseline for comparison.

Study Procedure

Participants joined the block-moving game hosted on a GitHub webpage. Each participant first completed a tutorial explaining the game mechanics, and their understanding of the task was assessed before they entered a waiting room to be paired with other participants, forming a team of three.

Each team was assigned to one of the eight experimental conditions. Teams either had access to real-time signaling for all levels or had no signaling available at any point. Each team of three progressed through four preset levels together. Gameplay for each level was limited to a maximum of 40 rounds. Teams made round-by-round decisions until either all blocks were placed into slots or the maximum number of rounds was reached.

Participants completed the four levels in approximately 27.5 minutes on average. At the end of each level, participants rated the level's difficulty, their satisfaction with the gameplay, and their perceived contribution to the team. After completing all four levels, participants filled out a short questionnaire about their experience working with the team and their impressions of each teammate.

Participants

471 participants were recruited through Prolific[1] (46% male, 53% female), aged 20 to 80 (Mean = 42, SD = 13). They all self-reported being over the age of 18 at the time of the experiment and are English speakers residing in the United States. Informed consent was obtained from all participants.

Measures

We collected behavioral, performance, and subjective measures to assess how groups coordinated. Performance was measured by the number of rounds required to complete each level, and the number of unsuccessful or stalled rounds (i.e., where no move could be executed). Coordination dynamics were captured through indicators such as how often players revised their proposals during the 5-second round, how quickly the team reached agreement within each round, and the proportion of rounds in which all players aligned on the same action. We also derived individual behavioral metrics,

[1] https://www.prolific.com/

including how frequently a participant initiated proposals and how often they adapted their plans in response to others.

At each level, we also collected participant ratings of perceived difficulty, satisfaction with the gameplay, and their personal contribution. At the end of the session, we collected additional ratings from participants, evaluating their experience working with the group and their impressions of each teammate or agent.

Results

In this section, we present the findings from our analyses examining the effects of real-time signaling on group-level coordination. Two key research questions were explored: (1) Does coordination efficiency improve when real-time intention signaling is available? and (2) Does coordination efficiency change over repeated task interactions?

We begin by reporting overall task performance across conditions as a function of level progression and the availability of real-time signaling. We then describe analyses on how access to real-time signaling and task progression jointly influence teams' coordination efficiency and their likelihood of completing a level within the allotted time. Finally, we characterize differences in coordination patterns between signaling conditions to provide a more detailed view of how real-time information shapes group behavior.

Real-time signaling increases the likelihood of successful level completion

Overall, the success rate in the no-signaling condition was 86.2% across all levels, with a mean completion time of 29.9 rounds. In contrast, teams in the real-time signaling condition achieved a higher success rate of 94.2%, with an average completion time of 27.8 rounds.

Importantly, due to the structure of the task, the data are right-censored: when a group failed to complete a level within the allowed limit, the number of rounds used was recorded as 40. Table 1 reports success rates and mean rounds to completion across signaling conditions and levels. Here, level refers to the order in which a group completed a specific layout during the experiment.

Although success rates were relatively stable across levels, the reduction in rounds to completion over time suggests that teams increasingly learned how to coordinate their actions more efficiently. However, because of the right-censored nature of the data, we do not treat mean rounds to completion as a primary performance measure and instead rely on time-to-completion analyses in the subsequent sections.

We conducted a Bayesian logistic regression using the JASP software packages (JASP Team, 2024) to investigate whether access to real-time signaling and progression across levels predicted the probability of successfully completing a level. The analysis provided strong evidence that real-time signaling increased success rates ($BF_{10} > 10$). In contrast, there was little evidence that level progression or the interaction between level progression and real-time signaling reliably influenced the likelihood of success. As the Bayesian

Table 1: Task performance by signaling condition and level. The table reports the average number of rounds taken by groups, including both successful and unsuccessful attempts. For groups that failed to complete a level, the maximum of 40 rounds was used when computing the average.

Condition	Level	Success (%)	Mean Rounds
No signaling	1	87	33
	2	90	28
	3	83	29
	4	85	28
Real-time signaling	1	95	30
	2	94	28
	3	94	27
	4	94	27

framework does not support clustered standard errors, we conducted a complementary frequentist logistic regression with standard errors clustered by team using the statsmodels package in Python (Seabold & Perktold, 2010). This analysis confirmed the effect of real-time signaling on task completion ($p<0.05$), suggesting that the result is robust to within-team dependence.

Real-time signaling leads to faster task completion

In addition to modeling whether teams successfully completed a level, we examined when completion occurred using survival analysis. Because of the experimental design, teams that failed to complete a level within the maximum of 40 rounds were censored at that limit, meaning that their true completion time is unknown beyond the cutoff. As a result, survival analysis is employed because it allows us to model time-to-completion while accounting for right-censoring.

We conducted a semi-parametric Cox hazards analysis using the lifelines package in Python (Davidson-Pilon, 2019), treating each round as a discrete time step and modeling the hazard of completing a level as a function of signaling condition and level progression. Standard errors were clustered by team to account for the non-independence of level attempts within the same team. Here, a higher hazard corresponds to a greater likelihood that a team completes the task at any given round.

As shown in Figure 3, the Cox model revealed a significant positive effect of real-time signaling on task completion (hazard ratio = 1.48, 95% CI [1.10, 1.98]), suggesting that teams with real-time signaling were approximately 49% more likely to complete the task at any given round than teams without signaling. In addition, level progression was associated with an increased hazard of completion (hazard ratio = 1.16, 95% CI [1.09, 1.24]), indicating that teams became faster at completing levels over repeated interactions.

Together, these results suggest that real-time signaling facilitates more efficient coordination over time and that teams benefit from learning across levels. The survival analysis in-

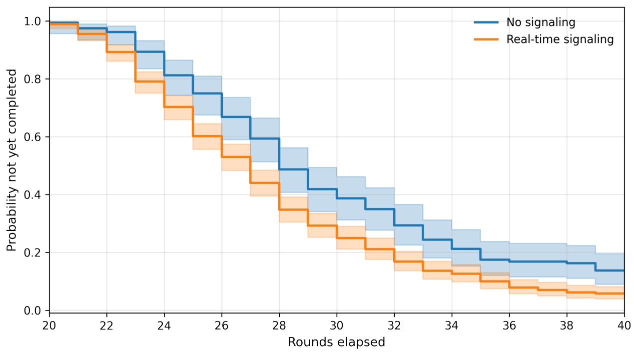


Figure 3: Kaplan–Meier survival curves showing the probability that a team has not yet completed a level as a function of rounds elapsed, shown separately for the real-time signaling and no-signaling conditions. Shaded regions indicate 95% confidence intervals. The x-axis starts at 20 rounds, corresponding to the optimal solution length, and ends at 40 rounds, the maximum allowed per level.

dicates that real-time signaling accelerates the propagation of coordination decisions within teams (Tump et al., 2020). As participants observe one another's intentions, shared plans can form and stabilize more rapidly, leading to earlier task completion.

Early-vote influence in ad hoc collaboration

To further inspect how real-time signaling shapes coordination within individual rounds, we analyzed the influence of early votes on subsequent alignment in the signaling condition. Because votes are not visible during the voting interval in the no-signaling condition, early-vote influence cannot reflect within-round coordination and was therefore not analyzed.

For each round, we identified the first vote cast and assessed whether at least one other player ended the round voting for the same action. Across all levels, early votes were frequently followed by at least one teammate, occurring in 78% of rounds.

We next examined early-vote influence in relation to the coordination demands of the action. When the first vote targeted a block that required two or three players to act jointly, the proposed action was ultimately executed in 74% of rounds. Additionally, we found that in 93% of such cases the executed move reduced the block's distance to the closer of the two target slots. This result suggests that early-vote following is not merely imitative, but is typically aligned with task-relevant goals. This pattern indicates that real-time signaling supports rapid alignment even for actions that require explicit multi-player coordination, highlighting how teams can quickly converge on shared plans during ad hoc collaboration.

Vote Revision Behavior Under Real-Time Signaling

To characterize coordination dynamics, we measured whether any player revised their vote within a round. A round was counted as having a revision if at least one vote changed during the voting period, and we report the proportion of such rounds aggregated across levels. Teams in the real-time signaling condition exhibited markedly stable behavior, 10% of rounds containing at least one vote revision. In contrast, teams in the no-signaling condition showed substantially higher vote revision, with 53% of rounds containing at least one vote revision. This difference suggests that access to real-time intention signals reduces the decision space for later voters and reinforces emerging coordination patterns. In the absence of real-time signals, teams appear to rely more heavily on private information, leading to frequent revisions and delayed alignment.

Coordination Failure Patterns

To understand how real-time signaling shapes coordination, we analyzed rounds where votes were cast but no block movement was executed. The no-signaling condition exhibited nearly double the failure rate (14.4%) compared to real-time signaling (7.8%).

The nature of failures differed markedly across conditions. In the no-signaling condition, conflicting directional votes accounted for 41% of all failures: cases where players agreed on which block to move but voted for opposite directions. In contrast, the real-time signaling condition showed a different failure profile: 71% of failures resulted from insufficient coordination on multi-player blocks.

These patterns suggest that real-time signaling primarily helps teams align on execution details, particularly movement direction while the challenge of converging on which block to prioritize persists across both conditions.

Discussion

This study examined how access to real-time intention signaling shapes coordination in ad hoc groups facing time-constrained collaborative tasks. Using a multi-player block-moving game, we compared teams that could observe teammates' voting intentions in real time with teams that only saw outcomes after each round. Our findings demonstrate that real-time signaling substantially improves coordination efficiency: teams with access to real-time information were more likely to complete tasks (94% vs 86% success rate) and did so more quickly.

Information Cascades in Coordination Contexts

Our results contribute to research on information cascades by exploring how cascade-like dynamics operate in settings requiring coordinated action. Traditional cascade research has focused on sequential decision-making where individuals observe prior choices and update their beliefs accordingly (Anderson, 2001; Huck & Oechssler, 2000; Çelen & Kariv, 2004). Our findings extend this work by showing that cascade-like alignment on early votes can be adaptive in coordination tasks under time pressure.

In the real-time signaling condition, early votes frequently attracted alignment from teammates (78% of rounds), and this alignment was particularly effective for actions requiring multi-player coordination (74% execution rate for 2-3 player blocks). Critically, 93% of these coordinated moves reduced the block's distance to the nearest slot, indicating that early-vote following was not merely imitative but typically aligned with task-relevant goals. This pattern goes beyond what vote visibility alone would predict: if alignment were a purely mechanical consequence of seeing others' votes, we would expect following behavior regardless of whether the proposed action advanced the task. The strong association between early-vote following and goal-directed movement instead suggests that players were selectively following votes that made strategic sense, which is consistent with accounts of joint action in which agents co-represent shared goals and use others' intentions to guide their own planning (Sebanz et al., 2006). This suggests that when the goal is synchronized action rather than accurate belief formation, rapid convergence through early signaling can facilitate efficient group performance.

Mechanisms of Coordination

Analysis of coordination failures revealed how real-time signaling shapes alignment. In no-signaling, 41% of failures involved directional conflicts where players agreed on which block to move but voted for opposite directions. In contrast, in real-time signaling teams, most failures involved insufficient votes on multi-person blocks. Notably, teams in the no-signaling condition still achieved relatively high success rates (86.2%), suggesting that outcome feedback and spatial task structure provide sufficient coordination cues in many cases.

These patterns suggest that real-time visibility primarily helps teams agree on execution details, particularly movement direction, rather than on higher-level decisions about which effort to prioritize. This aligns with work on coordination smoothers in joint action. Agents reduce execution uncertainty by making their own behavior more predictable to others (Vesper et al., 2010), which is a function that real-time intention signals directly support. Our failure analysis further suggests that the remaining challenge, converging on which block to prioritize, reflects a higher-level planning problem that persists even when fine-grained action alignment is supported. The benefits of real-time signaling are most pronounced when the coordination problem is one of execution alignment rather than goal selection. This finding is consistent with research showing that real-time visibility of others' actions supports spontaneous synchronization in dyadic interactions and facilitates convergence on shared plans in spatial coordination games (Oullier et al., 2008; Antonioni et al., 2014).

Learning Across Levels

Both conditions showed improvement across levels, with teams completing later levels more quickly than earlier ones. However, an important limitation of our study is that we cannot fully distinguish between different types of learning that may contribute to this improvement. Performance gains could reflect individual learning about task structure or social learning about teammates' strategies and tendencies, or both (Fisher & Wooders, 2020). Future work using computational modeling or individual transfer tasks would be needed to separate these contributions.

Implications and Future Directions

Our findings have implications for understanding ad hoc collaboration in real-world settings where teams must coordinate rapidly without extensive prior interaction. Our task instantiates a core challenge of ad hoc teamwork, coordinating with unfamiliar partners without pre-established conventions (Stone et al., 2010), and the benefits of real-time signaling we observe may be especially pronounced in precisely such fleeting-encounter settings. For strangers coordinating on the fly, real-time signals provide a critical scaffold that compensates for the absence of shared expectations. This interpretation is consistent with our learning-across-levels results: teams improved even without signaling over repeated interactions, suggesting that accumulated experience begins to substitute for real-time information as implicit conventions develop. This may be particularly relevant for distributed teams, human-robot collaboration, or emergency response scenarios where explicit communication is limited but actions must be quickly aligned.

The present findings were obtained in a three-person group setting, and the magnitude of the signaling benefit may vary with group size and decision structure. In dyads, ambiguity about who needs to coordinate with whom is reduced, potentially attenuating the benefit. In larger groups, real-time signaling may become even more valuable, though information overload could limit its effectiveness (Tump et al., 2020). Future work should also examine whether emergent leader-follower dynamics generalize across different group structures and task types. Future computational models (e.g., Bayesian joint planning or reinforcement learning frameworks) could formalize these coordination mechanisms and test generalizability across different team sizes, task structures, and signaling modalities.

These results also serve as a foundation for future research on human-AI coordination. Understanding how humans coordinate with and without real-time signaling provides a baseline for examining how AI agents might best integrate into human teams. Our failure analysis suggests that AI agents could potentially improve coordination by addressing different challenges depending on information availability: providing clear directional signals when real-time visibility exists, or helping establish robust cross-round conventions when it does not.

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