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Incoherent Robot Groups: How Divergent Motions within a Robot Group Predict Functional and Social Interpretations

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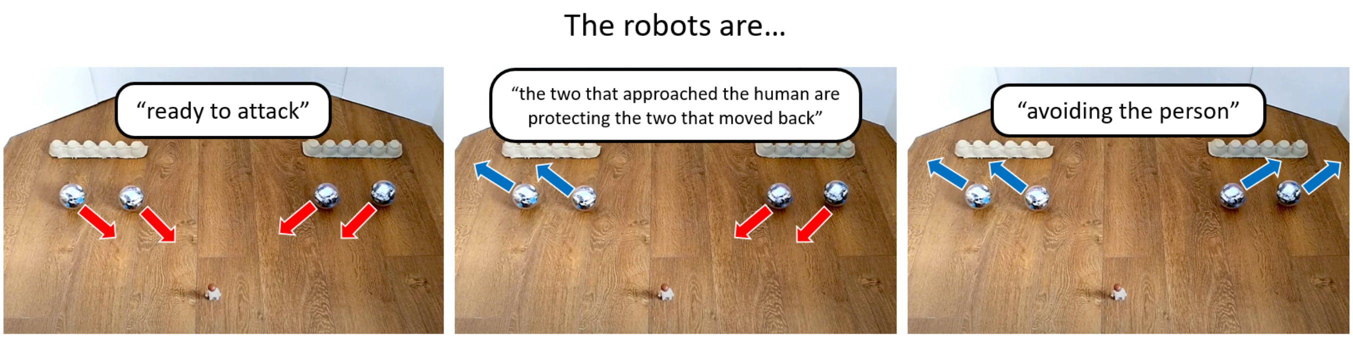

Figure 1: What are the robots doing? Descriptions of coherent and incoherent robot motion.

ABSTRACT

Research has found homogeneous robot groups can be intimidating, but few have studied the impact of intentionally incoherent robot group motion. This work explores incoherent group motion through an exploratory online user study, varying how robots move relative to a human figure entering the scene. Online participants (N=240 participants) rated twelve research conditions across various social and functional goals. Results showed coherent groups had the strongest communication signals, but incoherent motion can cue more complex communications. Coherent motion towards was threatening and blocking, and coherent motion away was avoidant and harmless. Coherent stillness was inviting. Subgroup size linearly affected communication strength.

CCS CONCEPTS

• **Computer systems organization** → **Robotics**; • **Human-centered computing** → *Interaction techniques.*

KEYWORDS

expressive motion, social robotics, multi-robot systems

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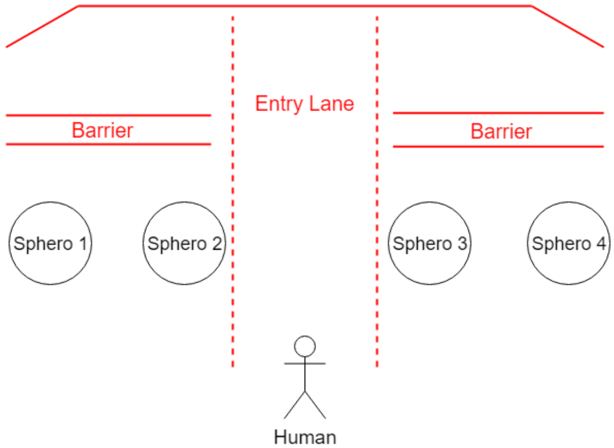
1 INTRODUCTION

Recent years have seen a rise in the number of robots in non-traditional settings, making it important to explore the effects multi-robot:human interaction. Ever-present in these interactions is motion, which automatically impacts human interpretation [11, 16]. There has been much research into single-robot expressive motion [3, 5, 10, 11, 20–22, 24], yet development of reusable features for multi-robot expressive motion is relatively nascent. Prior work has demonstrated the communicatory potential of coherent multi-robot motion [4, 6–8, 12, 14], varying overall robot motion characteristics and formations. This work adds a consideration of *incoherent* multi-robot motion to the literature, hypothesizing that contrasting social agents' actions would lead to higher order variations in social communication.

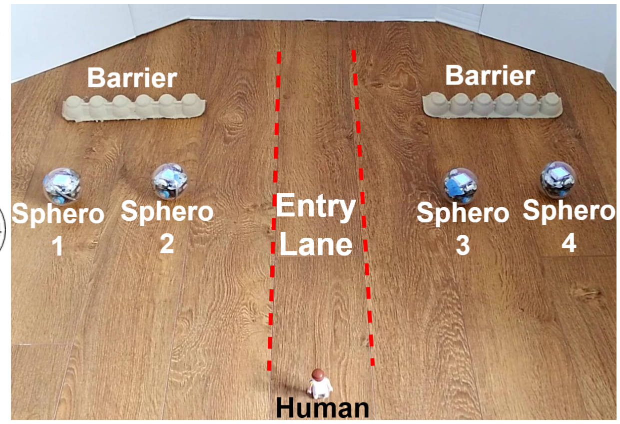
This work seeks to: (1) identify repeatable features of coherently and incoherently moving robot groups, and (2) understand strategies to vary these features for multi-robot:human interactions. The online video study presented in this paper examines how ***relative direction***, ***level of coherence*** and ***subgroup size*** affect participant impressions of robot social and functional communications. These manipulations expand on work exploring temporal and spatial synchronicity [23], by novelly incorporating explicit subgroup size and relative direction.

2 RELATED WORK

To understand how relative direction, level of coherence, and subgroup size can influence how people perceive multi-robot groups, we look to prior work in relative direction in expressive motion, human group dynamics, and coherence in multi-robot groups.



(a) Video study layout diagram



(b) Snapshot from the direction video study

Figure 2: Video study layout diagram and snapshot from a study video. In both, the floor plan, agent, and human are labeled.

Relative Direction and Trajectory in Expressive Motion: Relative direction has been explored for robot groups in work by Berger et al. [6]. Three robots were placed in front of a human figurine and performed different motions at two speeds. Participants rated these motions in an online study. Fast motion towards the figurine was seen as aggressive and confrontational, but slow motion was seen as welcoming and excited. Away and sideways motion were seen as fearing the figurine at both speeds.

Trajectory has been explored in single robots and multi-robot groups. People view single-robot direct motion as goal-oriented and confident [20, 21], while indirect motion is viewed as hesitant and confused [19, 21]. Similar results showed that trajectory of a multi-robot group affected a users ability to guess a robot group's goal [7].

Coherence and Group Dynamics in Human Behavior: People determine social groups through similar behaviors, culture, appearance, and identity [2, 28]. Humans within social groups often think in terms of in-group and out-group, which can often lead to a negative impression of perceived out-groups [2]. These larger social groups often contain smaller, independent social groups, which is referred to as clustering [25]. Clustering also occurs when subgroups have different functional roles within a larger group [2].

Coherent groups of humans are seen as powerful and influential, especially if large, and often have negative connotations, such as mobs and protests [31, 32]. The larger the group, the stronger their communication, influence, and in-group conformity [31, 32]. People are more likely to be influenced by information coming from majority groups than minority groups, [13] and group size directly affects how influential the group is [18]. These groups create pressure to conform to the group's standards, highlighting the communicatory and influential power that larger groups have over individuals and smaller groups [25]. However, coherence in groups is not always viewed negatively. For example, sports teams behave coherently with a collective goal, but this is positively viewed as teamwork, rather than a threat to others [26].

Coherence in Multi-Robot Systems and HRI: Coherence can be applied to multi-robot systems. Prior work has explored *when* how people perceive multiple robots as a cohesive group, showing that temporally asynchronous groups were perceived as the most expressive and spatially synchronous groups were perceived as the most cohesive [23, 30]. Studies have found coherent robot groups to be perceived as threatening, intimidating, and exclusionary, especially when the multi-robot groups act as out-groups relative to humans [12, 29].

3 ONLINE STUDIES OF COHERENCE

Using Sphero robots, we explored a scenario in which a human figurine approaches an entryway. The robots are distributed evenly on the right and left (Figure 2). These robots were chosen so we could explore x, y, θ expressive motion in multi-robot systems, as seen in previous work [19, 20]. This simple architectural setup has clear cognates in human-constructed environments. For example, it may appear that the robots are welcoming people or guarding the entry. In person, the Sphero robots are a comparable size to the human figurine, which approximates taller mobile robots that are closer to human height, such as delivery robots like Digit [9].

Research Conditions: We vary the robots' motion response to the figurine approaching and evaluate onlooker response in an online user study. The varied characteristics were: (1) relative direction (towards the figurine, away from the figurine, still), (2) level of coherence (low, high), and (3) subgroup size (one, two, three), as shown in Figure 3.

Video Studies: In Study 1, some robots move while others stay still to examine how number and activation impact communication. In Study 2, robot subgroups move in opposite directions to understand the impact of contrasting motions. Study 1 explores a higher level of coherence than Study 2. Participants viewed one video, then answered anchored scale and open-ended questions, focusing on how people interpret social and functional motivations of the robot group. All survey questions can be seen in Table 1.

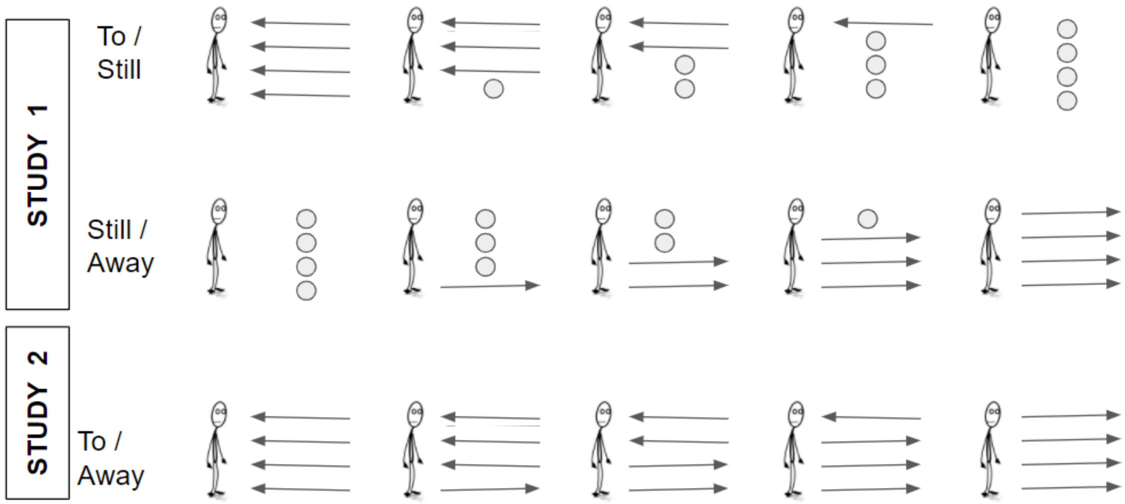


Figure 3: Conditions for Study 1 and Study 2. Stillness is represented by a circle, and motion represented by arrows pointing in the relative direction the robots move. Each circle and arrow denotes one robot performing that behavior.

Table 1: Online User Study Anchored Scale and Extended Response Questions

	Question
Anchored Scale	The robot group was [threatening / harmless].
	The robot group was [avoiding / inviting the human].
	The robot group was [not blocking / blocking the human].
Extended Response	What do you think the robot group was trying to do?
	What do you think is the motivation of the robot group?

4 RESULTS

Results for the anchored scale questions are plotted on a seven point scale from -3 (very [negative descriptor]) to 3 (very [positive descriptor]), showing the median, 25% quarantile, 75% quarantiles, and outliers by study condition. The anchored scale data was not normally distributed, requiring non-parametric testing. Kruskal-Wallis tests followed by pairwise Mann-Whitney U tests were used to calculate significance. Significant pairings are shown as * for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$. The x-axes study condition are shortened as follows: towards becomes 't', away becomes 'a', and still becomes 's.' The number before each direction indicates the subgroup size.

Threatening / Harmless: Coherent motion towards was significantly more threatening than all other conditions in both studies (Figure 4). Coherent motion away was significantly more harmless than almost all other study conditions.

Avoiding / Inviting: Coherent motion away was seen as significantly more avoidant than all other conditions. Coherent motion still was seen as significantly more inviting than all other conditions (Figure 5). In Study 2, there was a linear trend between subgroup number and how inviting or avoidant the group was perceived (Figure 5c).

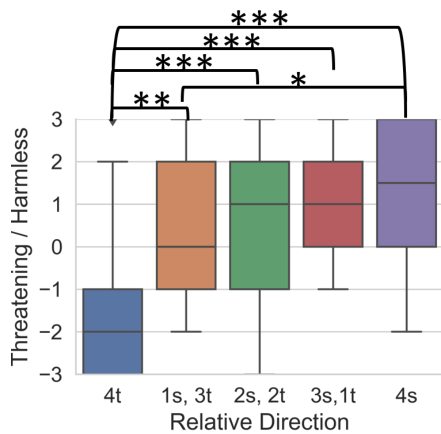
Not Blocking / Blocking: Coherent motion towards was significantly more blocking than almost all other study conditions. Coherent motion away was significantly less blocking than all other study conditions. Study 1 showed a linear relationship between subgroup number and perceived blocking (Figure 6).

5 DISCUSSION

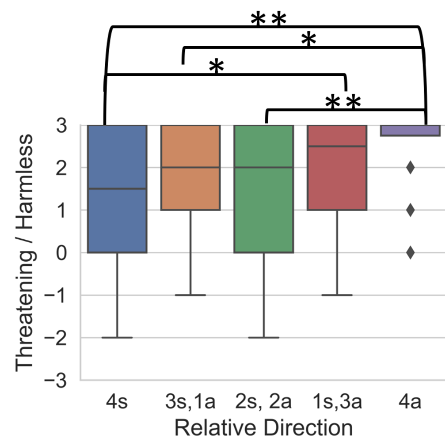
Coherent motion led to strong communicatory signals (Figures 4c, 5b, 6a, 6c). These results show coherent motion gave the clearest communicatory signals, while incoherent motion had large variances and lacked significant differences between the conditions. This communicatory strength may be due to the fact that all of the robots are exhibiting the same behavior. This phenomenon also appears in humans groups [13, 25, 27, 31]. In these human situations, groups exhibiting the same behavior send very strong communicatory signals. Our results expand the findings of work in human behavior to robot groups [13, 25, 31].

Coherent motion, especially towards, was perceived more negatively than incoherent motion, (Figures 4a, 4c, 5b, 5c, 6a, 6c). Coherent motion towards was the most threatening and blocking. Coherent motion away was the most avoidant. Directional coherent motion may lead participants to associate the robot group with crowd behavior associated with negative emotions, such as protests [15, 27] and evacuations [17], therefore perceiving the robots as aggressive or scared. This negative interpretation of coherent motion has been previously observed in multi-robot groups [12].

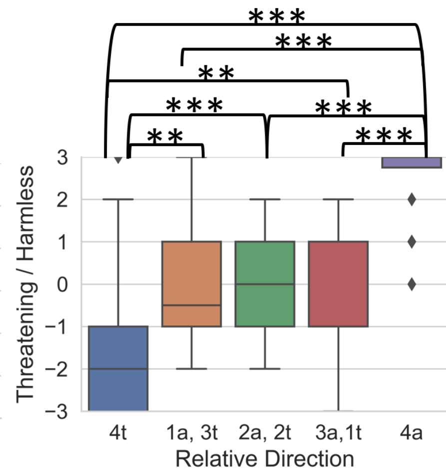
Coherent stillness and away motion were perceived positively (Figures 4b, 4c, 5b, 6c). Coherent stillness was the most inviting. Coherent away motion was the most harmless and least blocking. These positive interpretations may be due to spacial geometry. In humans, spatial geometry can change how we interact



(a) Study 1: Any Still Decreases Threat

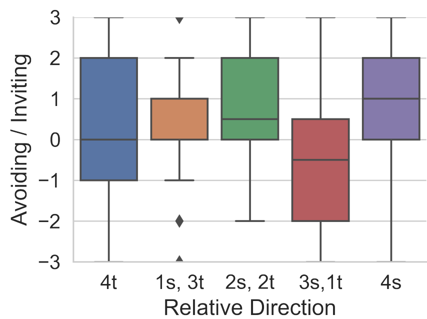


(b) Study 1: All Away Most Harmless

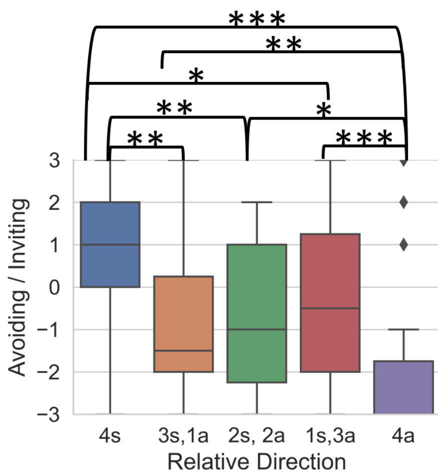


(c) Study 2: Coherent Most and Least Threat

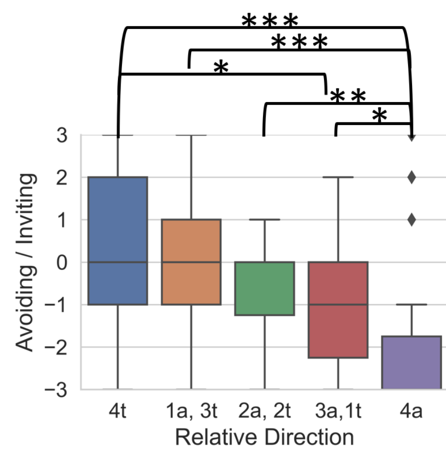
Figure 4: Threatening/Harmless Survey Response



(a) Study 1: One Toward Is Most Avoiding



(b) Study 1: All Away Most Avoiding



(c) Study 2: Towards/Away Clarifies Invitation

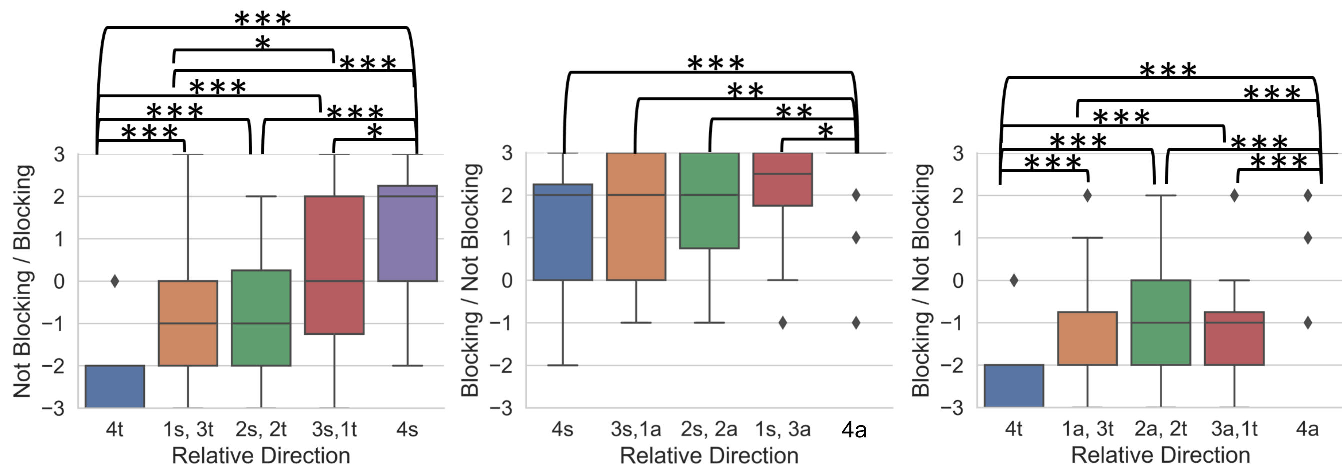
Figure 5: Survey response to "The robot group was [avoiding / inviting the human]."

[25], and this phenomenon may be occurring in human-robot interaction. Since there is a clear entryway in the physical study setup, stillness may have skewed positively because the robots were not impeding the person, while not actively helping them. Similarly, moving away may have appeared as moving to accommodate the human.

Subgroup size linearly affected communication strength (Figures 4a, 5c, 6a, 6b). Subgroups of three/one had stronger signals than subgroups of two. In human situations larger groups yield stronger communication [13, 25], and this effect may extend to robot groups.

Incoherent motion led to nuanced stories of the subgroup motivations. When both subgroups moved, participants described motivations of the subgroups separately. For example, one participant said "[o]ne group was trying to get away [and t]he other group was trying to go interact with the human." When there was a subgroup of one, participants did not always describe two fully independent sub-groups. For example, one participant said of one still/three away that the " robot group appears to be to meet someone new but not all of them wanted to."

Humans do not often behave as a singular coherent group [2, 25]. Incoherent motion may appear more social and natural, leading onlookers to perceive it as more expressive. Subgroups may reflect the clustering that happens in humans [2, 25] and lead participants to associate robot clusters with distinct attitudes and goals, and roles. This result supports the findings of St-Onge et al. [30], that asynchronous swarms were perceived as more expressive than synchronous swarms.



(a) Study 1: Towards Blocking, Still Not **(b) Study 1: More Away, Least Blocking** **(c) Study 2: Towards Blocking, All Away Not**

Figure 6: Not Blocking/Blocking Survey Response

6 CONCLUSION

This work expands previous concepts from coherence in multi-robot systems to include concepts from human group dynamics [2, 13, 25], such as subgroups, drawing on definitions of coherence in social psychology [1, 2]. These insights into how incoherent motion is perceived and what it communicates can be utilized by future researchers to vary functional and social communications when designing multi-robot systems in human spaces.

Future work will explore incoherent motion with in-person user studies. Future researchers can use these insights to send clear communications and vary their strength and complexity by using different subgroup sizes and similar or different motion characteristics. They can also alter their communications by using different relative directions and stillness.

Compliance with Ethical Standards This work was conducted under IRB #8724.

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