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Bots of a Feather: Exploring User Perceptions of Group Cohesiveness for Application in Robotic Swarms

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Abstract— **Behaviours of robot swarms often take inspiration from biological models, such as ant colonies and bee hives. Yet, understanding how these behaviours are actually perceived by human users has so far received limited attention. In this paper, we use animations to represent different kinds of possible swarm motions intended to communicate specific messages to a human. We explore how these animations relate to the perceived group cohesiveness of the swarm, comprised of five different parameters: synchronising, grouping, following, reacting, and shape forming. We conducted an online user study where 98 participants viewed nine animations of a swarm displaying different behaviours and rated them for perceived group cohesiveness. We found that the parameters of group cohesiveness correlated with the messages the swarm was perceived as communicating. In particular, the message of initiating communication was highly positively correlated with all group parameters, whereas broken communication was negatively correlated. In addition, the importance of specific group parameters differed within each animation. For example, the parameter of grouping was most associated with animations signalling an intervention is needed. These findings are discussed within the context of designing intuitive behaviour for robot swarms.**

I. Introduction

Robotic swarms allow for exciting new potentials in contexts such as exploration, rescue and surveillance missions, where these environments are often difficult for humans to access directly (e.g., caves, underwater, other planets). Although swarms can be deployed within these contexts with increasing levels of autonomy [1], often a human operator is still needed to monitor the status of the swarm and intervene when necessary [2]. This can include identifying when the swarm has encountered a problem (e.g., failure of one of the robots, low battery) or more general communicative messages such as signalling the beginning or end of a task. Classic methods for interacting with swarms include a Graphical User Interface (GUI) which can display the status of the robots and/or light or sound indicators. However, these devices may require training to use and are not necessarily always intuitive to the operator. Thus, there is still potential to explore other kinds of operator-swarm communication which can help facilitate these kinds of interactions.

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In contrast to other kinds of robots (e.g., social robots), swarms are not comprised of a single physical embodiment, nor do they typically possess anthropomorphic features such as eyes. In fact, a unique capacity of swarms is the ability to constantly shift in form and adopt new configurations [2]. On the engineering side, design of swarm robot behaviours is often bio-inspired, implementing features such as information sharing between individual robots [3]. However, less work has been done regarding how such behaviours are then perceived by humans. Nonetheless, human-swarm interactions, as in other human-robot interactions, are comprised of reciprocal interactions, where the swarm can be treated as a social entity capable of communication [4].

Human-Swarm Interaction (HSI) therefore aims to maintain awareness both of the swarm as an entity and the swarm members on an individual level. However, the need for the operator to continuously monitor the swarm and track macro-level changes can lead to several constraints in cognitive load and situational awareness [5], [6]. For instance, when there are multiple objects to keep track of, even if they are few in number, difficulties in detecting changes in the status of the swarm may arise (e.g., [7], [8]). As operators may not always be co-located with the swarm, how the operator visualizes and interprets the movements of the swarm during remote interactions also needs to be considered [9], [10].

Consequently, swarm behaviours should be designed such that they can be easily identified and understood by any operator, from any location [11], [8]. Ideally, such behaviours would also be interpretable across contexts and tasks and not limited to a specific configuration or type of robot. That is, these behaviours, aka *motion-invariants* [12], should be inherent to the properties of swarms in general. We can then potentially use these behaviours to either supplement or replace typical GUIs for swarm control to make the interaction with the operator more intuitive.

To begin exploring how such motion-invariants could be designed, we can consider features of human visual perception. As emphasized by Gestalt principles, human perception is naturally inclined to form organized groups, patterns and objects from visual information. Studies by [13], [14] show that the visual perceptual system integrates elements of a scene as part of the same structure when these elements are close together and move coherently, i.e., at the same speed. That is, *group cohesion* occurs when the swarm is perceived as a single unified entity. To this point, [15] found that increasing the number of robots in a swarm is not detrimental to the operators cognitive load when control is performed on the entire swarm. Additionally,

[16] showed that as swarm cohesion decreases, changes in swarm motion are less detectable. Individual Gestalt factors, such as similarity, proximity, symmetry, and synchrony are also not specific to static visual information, but apply also to moving objects [17]. Group cohesiveness can then further be conceptualised as a multifaceted construct, made up of several different parameters which both individually and collectively contribute to the perception of the swarm [10].

We can potentially leverage group cohesiveness to inform the design of swarm behaviours. Although previous works have established that robotic swarms are able to convey different kinds of messages through their behaviour [10], [4], [18], these have so far followed a mostly bottom-up approach, manipulating mechanical features of the swarm such as velocity, trajectory, and inter-robot distances. How these behaviours are translated on a psychological and cognitive level, and how this can subsequently influence the interpretation of the swarm's message/s has yet to be explored. In this work we aim to address this gap by investigating how group cohesiveness is related to the perceived communicative intent of robotic swarms.

II. The Current Study

We use animations to represent different swarm behaviours and evaluate their perceived group cohesiveness. In an online user study, participants viewed a sequence of 9 different animations intended to represent different swarm communicative intents (initiate communication, intervention needed, low battery, broken communication, no problem, close communication). For each animation, participants were asked to evaluate how much the behaviours of the swarm correspond to different parameters of group cohesion (synchronising, grouping, following, reacting, and shape-forming).

III. Method

A. Participants

Ninety-eight french-speaking participants (38 women) were recruited to participate in the study via word of mouth. The majority ($N = 72$) were aged between 18-29, followed by $N = 15$ between 30-39, $N = 2$ between 40-49, $N = 8$ between 50-59 and $N = 1 < 18$. Participants had varying levels of familiarity with robots. Participation was completely voluntary and did not include compensation. The study was approved by the research ethics committee at ETS Montreal.

B. Materials

Nine GIFs were created exploring six different kinds of swarm communicative messages; initiating communication, closing communication, no problem, intervention required, low battery, broken communication[1]. These messages were chosen based on previous work exploring communicative intent in robot swarms [10] and were designed in collaboration with domain experts (graphic design, robotics, and psychology students) and thus followed a "top-down" approach to generating robot behaviours: design the motion *before* the swarm behavior. Whereas previous works aimed at assessing the perception of common swarm behaviors (e.g., flocking, rendez-vous; [18], [19]), we designed pure motions that will later be implemented as swarm behaviors. Previously, we validated to what extent each of the 9 animation sequences succeeded in communicating different messages[2]. A description and image of each animation, along with the intended and perceived messages from the validation analysis, are presented in Table I.

C. Design and Procedure

We employed a one-way within-groups design, with type of animation (Sequences 1-9) being manipulated. The study was conducted online and took approximately 15 minutes to complete. After entering the survey and giving their consent to participate, participants were shown the animations in one of 3 different predefined orders. After each animation, participants were asked to rate, first, what messages they felt the robots were trying to communicate (initiating communication, closing communication, no problem, intervention required, low battery, broken communication) and second, to what extent they felt the animation corresponded with each of the 5 parameters of group cohesiveness (synchronising, grouping, following, reacting, and shape forming). All items were rated on a 5-point likert scale from *1-Strongly Disagree* to *5-Strongly Agree*. The original and translated versions of items can also be found online. After viewing the animations, participants were also asked to complete some demographic questions (age, gender, profession), as well as 3 questions assessing their familiarity with video games, physical coordination (e.g., dance, gymnastics) and digital animation (*0-never, 5-regularly*).

IV. Analysis Plan

In this work we extend on our previous findings, which related the designed animations to the perceived messages. Here, we first evaluate to what extent the different communicative messages were associated with the parameters of group cohesion, and second, explore whether and how the animations differed along the parameters of perceived group cohesiveness. We also control for participant's familiarity with video games ($M = 3.27, SD = 1.83$), physical coordination ($M = 2.27, SD = 1.66$), and digital animation ($M = 1.77, SD = 1.69$). Full results are available online[3].

V. Results

A. Correlations

We first constructed a correlation matrix between the parameters of group cohesiveness and the perceived communicative messages using Kendall's τ ranked correlations, see Table II. The message "initiate communication" was most associated with group cohesiveness, demonstrating strong positive correlations with all parameters. This was followed by the message signalling no problem, which was positively

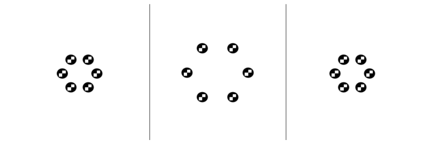
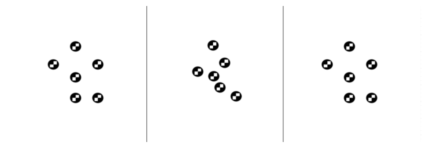
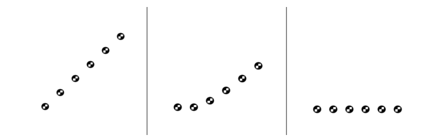
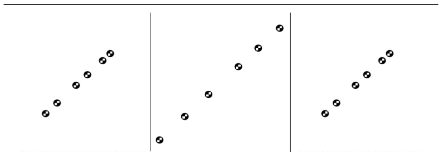
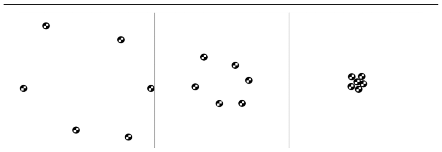
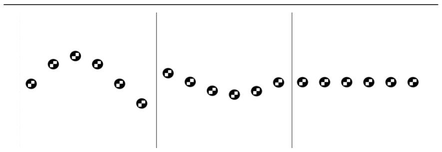
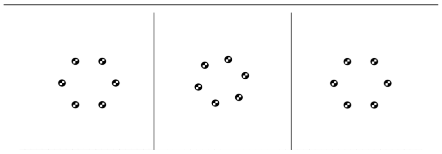
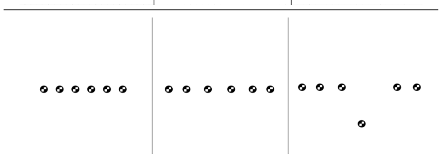
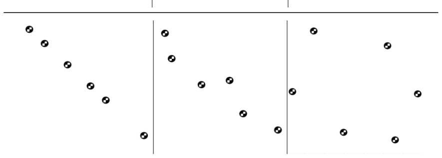
[1]see `initrobots.ca/peerm` for full animations

[2]Complete results here: `https://initrobots.ca/RSRW/`

[3]`initrobots.ca/gcrs`

TABLE I

SUMMARY OF THE NINE DIFFERENT SWARM MOTIONS

Animation	Image	Intended Message	Perceived Message/s	Description
1		Initiate Communication	Initiate Communication Intervention Required	Robots start spread out, then come together and pulse in a circle
2		Intervention Required	Intervention Required Low Battery	Half the robots stay still and vibrate whilst the other half move around them.
3		Low Battery	Close Communication Low Battery No Problem	The robots start in a diagonal line then fall in a wave
4		Initiate Communication	Initiate Communication	The robots form a diagonal line which contracts and expands
5		Intervention Required	Intervention Required	The robots cluster in a tight group and vibrate
6		Low Battery	Initiate Communication	Oscillating wave that slowly decreases in amplitude
7		No Problem	Initiate Communication No Problem	A circle moving in slow oscillations with counter-clockwise rotation
8		Broken Communication	Low Battery Intervention Required Broken Communication	Robots form a line which one robot drops away from
9		Close Communication	Close Communication	Robots disperse into random directions

associated with all parameters except *reacting*. Intervention needed was positively correlated only with the parameter of *grouping*. Conversely, broken communication was the message least associated with group cohesiveness, demonstrating negative correlations with all parameters except *following*. The low battery message also showed negative correlations with the parameters of *synchronising* and *shape forming*. Closing communication showed a weak negative correlation only with the parameter of *grouping*.

B. Linear Mixed Model

To explore how the different parameters of group cohesiveness corresponded with the designed animations, we constructed a linear mixed model [20]. The model included fixed effects of animation, group parameter, familiarity with video games, physical coordination, and digital animation, as well as a random intercept to account for individual participant differences (Model 1). All post-hoc tests were conducted using false discovery rate (FDR) corrections.

TABLE II
CORRELATIONS BETWEEN GROUP PARAMETERS AND PERCEIVED COMMUNICATIVE MESSAGES

	Initiate Communication	Close Communication	No Problem	Intervention Needed	Low Battery	Broken Communication
Synchronising	0.23***	0.04	0.13***	-0.036	-0.1***	-0.12***
Grouping	0.18***	-0.068*	0.056*	0.073**	-0.022	-0.11***
Reacting	0.2***	0.023	0.045	0.011	-0.053	-0.063*
Shape Forming	0.12***	-0.036	0.095***	-0.008	-0.094***	-0.11***
Following	0.11***	0.046	0.092***	-0.001	0.0014	-0.015

* Significant at the $p < .05$ level, ** Significant at the $p < .01$ level, *** Significant at the $p < .001$ level

Model 1 revealed significant fixed effects of animation and group cohesiveness, but no effect of familiarity with video games, physical coordination, and digital animation, Pseudo $R^2 = 0.12$, see Table III. We also constructed a second linear mixed model with the interaction term between animation and group parameter (Model 2). Comparison of the two models indicated that including the interaction term provided a better fit for the data ($\Delta AIC = 70$).

To follow up the main effect of animation, we conducted post-hoc pairwise comparisons between each of the 9 animations. Seq. 7 was rated higher on group cohesiveness than almost all other sequences, with the exception of Seq. 6. Although there were no differences between Sequences 3, 4, and 6, all three were rated as significantly more cohesive than all other sequences. There was no difference between Seq. 1 and Seq. 2, nor between Seq. 2 and Seq. 5, or Seq. 5 and Seq. 8. Seq. 1 was rated more cohesive than Sequences 5, 8, and 9.

For the interaction between animation and group parameters we conducted follow-up post-hoc tests comparing each of the 5 group parameters within each animation, see Fig. 1.

For Seq. 1, *synchronising* was significantly higher than all other parameters. The next highest parameter was *shape forming*, which was significantly higher than *following*, but not *grouping* or *reacting*. There was also no difference between *grouping* and *reacting*, although both were rated significantly higher than *following*.

Seq. 2 followed a different pattern, with *following* being rated significantly lower than all other parameters. No other comparisons were significant.

For Seq. 3, *reacting* was significantly higher than *shape forming* and *following* (but not *synchronising* or *grouping*). This was followed by the parameter of *synchronising*, which was also rated significantly higher than *shape forming* and *following*. No other comparisons were significant. The high rating of *reacting* here is likely due to the waterfall-like motion of the robots, each falling one after the other.

Seq. 4 had *synchronising* as it's highest rated parameter, which was significantly different from all other parameters except *forming figure*s. There was no difference between *shape forming*, *grouping*, and *reacting*, however all three were rated significantly higher than *following*.

Seq. 5 again showed a different pattern, with *grouping* being rated significantly above all other parameters. *Synchronising* was the next highest parameter and was also rated significantly higher than *reacting*, *shape forming*, and *following*. *Reacting* was rated significantly higher than *following*, but not *shape forming*. There was no difference between *shape forming* and *following*.

Within Seq. 6, the parameters of *synchronising* and *reacting* were rated significantly higher than all other parameters, although there was no difference between the two.

Seq. 7 showed no difference between the parameters of *synchronising*, *grouping* and *shape forming*, although all 3 were rated significantly higher than *reacting* and *following*. In turn, *reacting* was also rated higher than *following*.

For Seq. 8, *synchronising* was rated significantly higher than *grouping* and *following*, but not *reacting* or *shape forming*. *Reacting* was also rated significantly higher than *grouping*. The high rating of reacting may be explained by the fact that one of the robots drops away from the others.

Seq. 9 showed a similar pattern to Seq. 8, with *synchronising* again rated significantly higher than *grouping* and *following* but not *reacting* or *shape forming*. *Reacting* was also rated higher than both *grouping* and *following*, as was *shape forming*. There was no difference between *reacting* and *shape forming*, nor *grouping* and *following*. This animation showed the robots quickly dispersing, accounting for the low ratings of grouping and following.

VI. DISCUSSION

In this study we used animations representing robotic swarms to explore how different parameters of group cohesiveness relate to perceived communicative messages, as well as how such motions contribute to the perceived swarm cohesiveness. Previously, we also explored which messages were associated with each animation. Here, we build upon these findings by introducing the concept of group cohesiveness as a potential link between the individual motions and the perceived messages. In doing so, we can explore whether and how cognitive features of the animations influence the communication between the swarm and the user.

We found clear differences in overall group cohesiveness of the animations. In particular, Seq. 7 was perceived to have among the highest levels of cohesiveness, whereas Seq. 9 had the lowest. In Seq. 7 all robots were performing the same movement, in the same direction, at the same speed, potentially explaining why this animation was seen as having the most cohesiveness [13], [14]. Sequences 3, 4 and 6 also all represent all robots in the swarm executing the same movement. Again, the repetitiveness of the movements in all cases may explain why these animations were rated higher

TABLE III

LINEAR MIXED MODELS FOR FIXED EFFECTS AND INTERACTION OF ANIMATION AND GROUP PARAMETER

Variable	**Model 1**						**Model 2**	
	b	*se*	*t*	*F*	*p*	*95% CIs*	*F*	*p*
(Intercept)	4.07	0.18	22.45		$< .001$	[3.72, 4.43]		
Video Games	-0.05	0.04	-1.11		.27	[-0.12, 0.03]		
Physical Coordination	0.05	0.04	1.22		.23	[-0.03, 0.13]		
Digital Animation	0.03	0.04	0.74		.46	[-0.05, 0.12]		
Animation				354.34	$< .001$			
Group Parameter				326.63	$< .001$			
Animation x Group Parameter							195.31	$< .001$
AIC	14031.15						13960.97	

Notes: F-values are reported where it is not possible to obtain a single b-value (i.e., for effects with > 2 levels and interactions). Interaction values report unique variance over and above main effects.

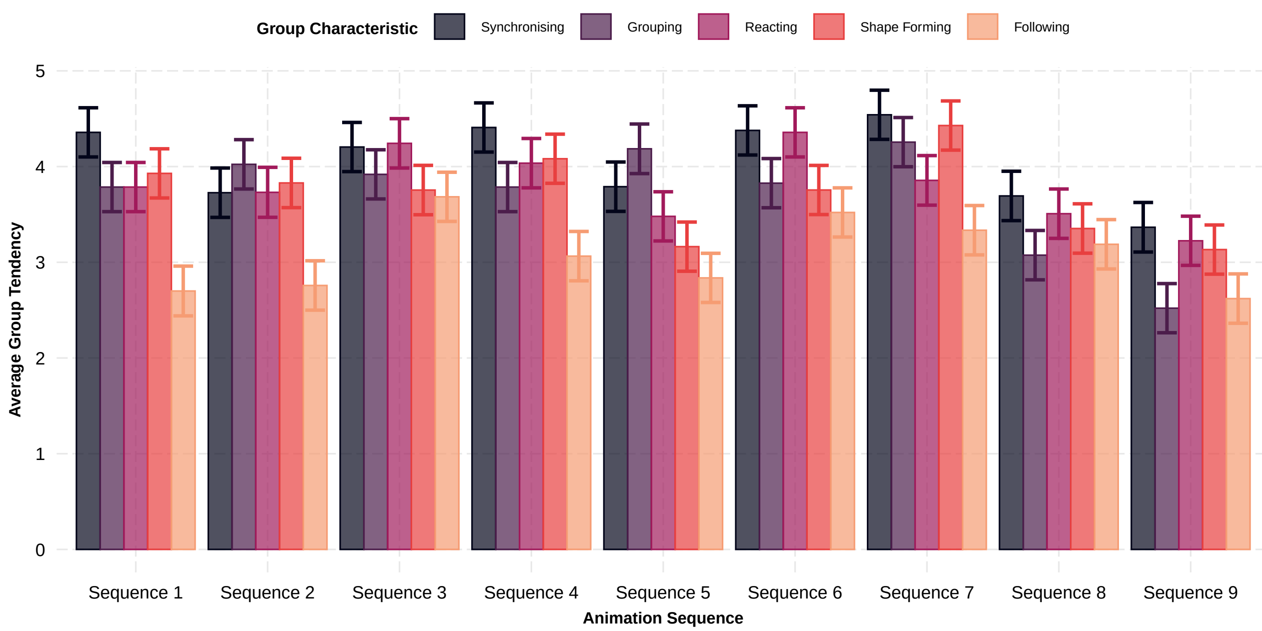


Fig. 1. Mean ratings of each group parameter within each animation

overall on perceived cohesiveness. These movements were also all slower compared to most of the other sequences, communicating a sense of deliberateness which could have further contributed to the sense of group cohesion. For Seq. 1, it is possible that the increased speed of this animation decreased the perceived cohesiveness compared to the other similar, but slower, animations. The remaining Sequences (2, 5, 8, and 9) all involved the robots moving at a high speed, with one or more robots performing different actions. The lack of coordination between the robots combined with faster movements likely contributed to a lower sense of group cohesiveness for these animations.

We can interpret the interaction between the animations and parameters of group cohesiveness within the context of the messages the animations were intended to communicate. First, Sequences 2 and 5 were both designed with the message of “intervention required” in mind. In fact, both of them succeeded in communicating this message (with the caveat that Seq. 2 overlapped with “low battery”; however this action in itself necessarily implies an intervention). They were also the only two animations where grouping was the highest rated parameter. This is again confirmed by the correlations, where the intervention needed message showed a strong positive correlation only with the parameter of grouping. Thus, grouping could be considered as a swarm motion-invariant associated with the need for intervention.

Seq. 9 also achieved its intent to communicate ending the interaction. The low ratings of cohesiveness make sense in this context - ceasing coordinated motion could be interpreted as a signal that the interaction is over. The negative correlation between the close communication message and the parameter of grouping further supports this idea.

Seq. 7 mostly succeeded in communicating its message of “no problem”, with some overlap with “initiate communication”. However, there was no clear group parameter which could be identified as defining this motion - synchronising, shape forming, and grouping were all rated equally. The "no problem" message itself was also highly correlated with all parameters except reacting. Combined, these findings could indicate that once a swarm of robots has started moving, so long as the behaviours remain consistent, no intervention is seen as necessary.

Sequences 1 and 4 were validated as initiating communication. Both animations had synchronising as the highest rated group parameter. Seq. 6, although conceptualised as low battery, was in fact also associated with initiating communication and had synchronising as its highest rated parameter, replicating the pattern seen in Sequences 1 and 4. The message of initiating communication itself was not only correlated with synchronising, but with all group parameters. These findings verify the idea that synchronisation is perceived as an intention to communicate [21].

Seq. 3 was intended to communicate the message of "low battery", however, in reality it failed to distinguish between the low battery, no problem and intervention needed messages. Similarly, Seq. 8 demonstrated confusion between low battery, intervention needed, and broken communication messages. Here, the group parameters were equally difficult to interpret for both animations, with both sequences showing similar ratings between reacting and synchronising. As a result it is difficult to draw strong conclusions for the motion invariants for these animations.

Additionally, we did not find any relationship between participants' familiarity with video games, physical coordination, or digital animation and the parameters of group cohesiveness. This could suggest that designing swarm behaviours based on cognitive features can provide a potential advantage over GUI-based systems, where these features may be more intuitive and do not require specialised training to interpret.

The results presented here contribute to our understanding of human-swarm interaction by providing insight into how such behaviours are interpreted on a perceptual level. In particular, group cohesion was identified as a potential mediating link between swarm behaviour and perceived messages. Future work will endeavour to test this relationship more explicitly, as well as explore links with other psychological factors such as perceived cognitive load. Ultimately, these behaviours are also intended to be implemented and tested on real robotic swarms.

VII. Conclusion

In this study we aimed to explore the relationship between swarm motions and perceived group cohesiveness. We found correlations between gestalt-inspired parameters of group cohesiveness (synchronising, grouping, following, reacting, and shape-forming) and different communicative messages, supporting the idea that human visual perception can be leveraged to inform the design of swarm behaviours. Additionally, animations associated with specific messages were differently related to individual group parameters, potentially forming the basis for swarm motion-invariants. These results can help provide a starting point for the design of intuitive group motion in real robotic swarms.

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