Deliberative Democracy with Robot Swarms

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***Abstract*— Decision-making among groups of humans can benefit from open discussion and inclusion of a diversity of opinions, promoting deliberative democracy. In this work, we test whether a swarm of robots can help facilitate decision-making by visually representing the diversity of opinions. We used a swarm of robots we built, called MOSAIX, that consists of 4-inch touchscreens-on-wheels robots called Tiles. The robots acted as physical avatars for opinions, helping them travel and mix together. We recruited 46 participants split into groups of 7 and 8 to test whether the robot movement had an impact on the decision-making process versus using the robots stationary in the participants' hands akin to smartphones. Furthermore, we wanted to test whether the participants felt comfortable expressing their opinion through the robots. Results show the participants indeed felt comfortable using the robots, and user engagement increased with the movement of the robots. The difference between the participants' first and last opinions also increased with the movement of the robots. We believe that robot swarms have not been used before to facilitate decision-making among a group of people. Therefore, our contribution is in testing the possibility of how and whether using a moving robot swarm helps humans reach a decision.**

I. Introduction

Group decisions are prominent in everyday life. Decision-making can benefit from open discussion and inclusion of a diversity of opinions. The opportunity for technology-driven decision-support systems has emerged as decisions become more complex and involve more people, many of whom may feel excluded from the conversation for reasons of socioeconomic status, identity or personality. The movement for "deliberative democracy" [1], [2] aims to boost the public's understanding of complex issues and builds community relationships. Fundamental to this are personal encounters between participants. Yet many technological tools involve software on computers, phones, or tablets, that take away from meaningful human interactions. Instead, robot swarms, through their ability to move within human environments, have the potential to visibly convey consensus, to display a participant's opinion and to aggregate information through local communication, engaging participants in decision-making. While most swarm robotics has been constrained to the laboratory environment, we are now at a stage where hundreds of simple robots can be produced for real-world settings alongside humans. With this work, we aimed to test whether the swarm could be an effective support system in deliberative democracy.

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To test this, we used a swarm of robots, "MOSAIX" [3], consisting of robot "Tiles" - which are 4-inch touchscreens-on-wheels robots with proximity sensors for obstacle avoidance - to act as avatars for the participants; representing their opinion and carrying it around for other participants to observe. Studies previously have shown that using a robot increases group engagement and problem-solving skills [4], as well as increases group interactions [5]. Similarly, our aim was to see whether the movement of many robots (rather than one) while visually representing opinions, in contrast to static devices, help in facilitating decision-making by increasing participant engagement. We anticipated this could be because humans can see others' opinions moving and mixing together, helping them reach a decision. Also, they could potentially feel more comfortable expressing their opinion, because as soon as the participant enters their opinion onto a robot, the robot mixes with other robots, obscuring the origin of individual opinions.

Therefore, we carried out a user study with 46 participants split into groups of 7 and 8, which was reviewed and ethically approved by the Faculty of Engineering Research Ethics Committee (FREC) at University of Bristol. The user study had two experimental conditions. First, the *moving* condition, where after a participant entered an opinion onto the Tile, the Tile moved randomly, displaying the opinion among other Tiles in the swarm with other people's opinions. This allowed for the opinions to travel and mix together. Second, the *stationary* condition, where each Tile acted as a static smartphone or tablet; each user held one Tile in their hand to enter their opinion (hence, the Tiles were static in the user's hand). We used a non-mobile Tile rather than a phone/tablet to control for the general novelty of the Tile itself in the subsequent trials, and to keep the interaction modality the same (physical and interface). This focuses the study on how *stationary* versus *moving* states of the technology (Tiles) enables decision-making. Our user study followed a within-subjects design, meaning that all participants experienced both conditions.

II. Related Work

Group decisions are made daily and are often social in nature. When done well, the "Wisdom of Crowds" can lead to better decisions than those made by individuals [6]. Pooling of information, open discussions, and a diverse group of people can all facilitate good decision-making [7]. As group decisions grow in size, and complexity, the addition of decision-support systems has been considered to facilitate the process [8]–[10]. Also, systems facilitating knowledge transfer between individuals in a group have been built before [11]. These systems however are mostly based on software, which may take away from in-person open discussions [12]. This work specifically implements a swarm robotic system to facilitate decision-making dynamics between people in physical settings.

Robotic systems often use decision-making algorithms, such as those being used in autonomous vehicles [13], to accomplish tasks. Decisions made by robots with a human input have also been researched [14], as well as the effect of robot decisions on tasks done by human-robot teams [15], [16]. In our work, we are instead interested in how a swarm of robots, rather than individual robots, can facilitate, rather than perform, decision-making done by a swarm of people. Robot swarms could serve as interactive decision-making support systems, facilitating meaningful human interactions by moving through a crowd, and providing a visual feedback of the state of consensus.

Robot swarms can now be built with hundreds of robots with relative ease [17], and have demonstrated effective decision-making capabilities [18] inspired from nature [19]. Algorithms for consensus-reaching in robot swarms have also been studied previously [20]. Collective decision-making in deliberative democracy [1], [2] could benefit from the development of a swarm robotic platform to facilitate the mixing of robot and human swarms. This is where the novelty of our work lies; through using robot swarms to facilitate decision-making among humans. Furthermore, robot swarms are decentralised and scalable to large numbers [21]. Similarly, decision-making in humans is also a decentralised process that may be done by large numbers of people. Decentralised and scalable swarms of robots may provide a complementary tool for facilitating decision-making among humans, whose numbers can vary.

Human-swarm interaction is a growing field in the swarm robotics research [22]. Research in human-swarm interaction has previously been conducted in different contexts, such as in swarm guidance [23], [24], radiation search [25], forest firefighting [26], and art [27], [28]. Our work instead explores human-swarm interaction in the context of human-swarm decision-making.

In general, multi-human multi-robot systems are very scarcely researched. Most human-swarm interaction systems are studied as single-human multi-robot systems [22]. Also, previous research in human-robot interaction focused on single-human single-robot systems, with more research being made on multi-human single-robot systems [29]. Therefore, our contribution also lies in studying multi-human multi-robot dynamics through the context of decision-making.

III. Hypotheses

With our user study, we aimed to test whether a swarm of robots can serve as a decision-support system in human group decision-making scenarios. Our two hypotheses are:

1) Participants feel comfortable using the robots to express their opinions.
2) Moving robots have a significant impact on an individual's engagement and decision-making.

These two hypotheses were tested through analysing data acquired from robots in two experimental conditions, *stationary* and *moving* (see Fig. 1), as well analysing responses to a post-study questionnaire. To simulate a democratic activity, participants were asked challenging questions with immediate importance to their research or studies. These aspects are explained in detail in the next section.

IV. Methodology

A. Participants

Overall, we had 46 participants (39 males, 6 females and 1 non-binary). The user study took place on University of the West of England's campus. Due to COVID-19 restrictions,

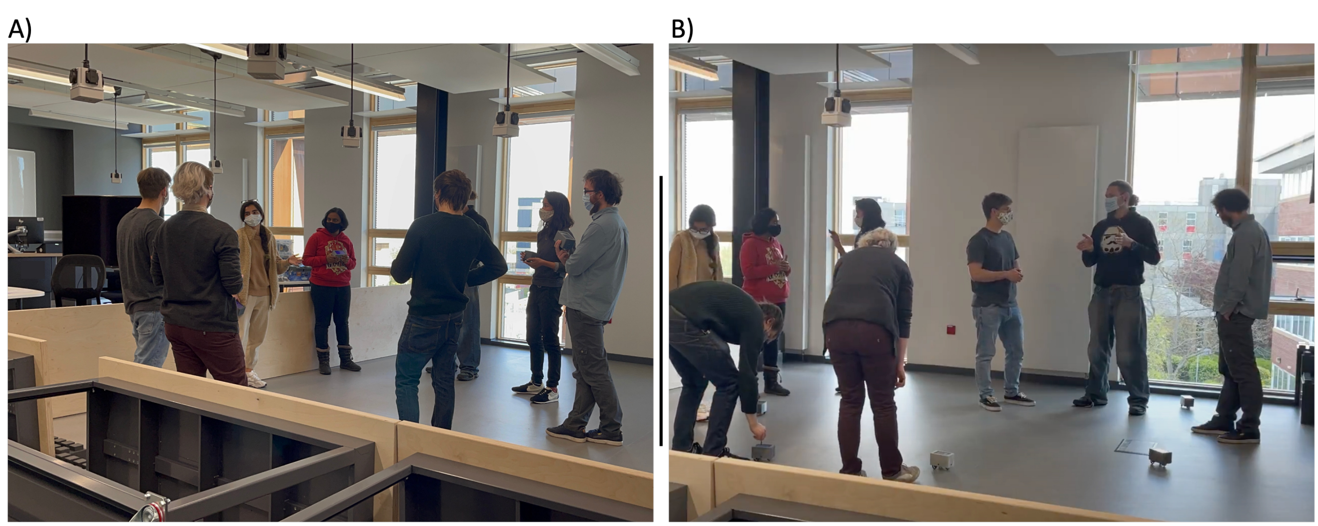

Fig. 1. A) Stationary condition: each participants holds and keeps a Tile with them. B) Moving condition: Tiles are moving randomly in the arena and participants can pick any Tile to enter their opinion.

it was difficult to recruit participants, and all participants recruited were either students of a robotics Masters program, or researchers working in Bristol Robotics Laboratory. Therefore, participants were mostly familiar with robots. Participants were asked to rate their familiarity with robots on a scale from 1 to 5 where 1 is least familiar and 5 is most familiar (μ=3.74, σ=1.22, median=4). The participants were from different age groups (16 participants were 18-23 years old, 22 participants were 24-30 years old, 5 participants were 31-40 years old and 3 were older than 40). Participants were recruited in groups of 7 and 8 (2 groups of 7 and 4 groups of 8). Due to COVID-19 restrictions, we aimed to decrease the number of participants per group to fit in a room while still maintaining social distancing measures. Therefore, groups of maximum 8 people were deemed appropriate for the space (5m$\times$6m) where we conducted the experiments.

B. Experiment Design

The participant groups did the experiments at different times. Participants went through the 2 experimental conditions. First, a *moving* condition, where robots moved around, collecting opinions from participants. Second, a *stationary* condition, where each participant kept their own robot as if it were a personal phone. This is shown in Fig. 1. In each condition, the groups were asked one of two questions: “What percentage of in-person vs online teaching do you think the university should offer next year?” or “What percentage of coursework vs exams do you think the university modules should offer?”. The order of conditions was alternated with each group as well as the order of questions to avoid influences on internal validity and to reduce the impact of learning effects on the data. Before the study began, participants were briefed on the study and its aims, asked to read a participant information sheet, sign a consent form, pick up a random stylus (which had a sticker on it with their participant number) and fill in the pre-study questionnaire (which was based on the Big-5 personality traits test [30], since we were interested in any apparent predisposition of participants). Then, the participants were told the question, told they had 10 minutes to discuss (which would be cut short if they reached consensus), and told to enter their opinions on the robot as much as they liked (they could also change their opinion).

Depending on the experiment order, if the first condition was *stationary*, the participants were asked to pick up a robot from the floor and keep it with them throughout the entirety of the first experiment. To enter an opinion, the participant had to click on the screen. The robot would then prompt the participant to choose their participant number, as shown in Fig. 2A. Then, they were presented with a screen that showed them the question and buttons that have the options to click on (from 0-100%, in increments of 10%), as shown in Fig. 2B. Then, for both conditions, the robot would show the last opinion entered as shown in Fig. 2C. In order for a participant to enter a new opinion, they had to press on the screen to repeat the process.

In the *moving* condition, participants could use any robot to enter their opinion, while in the *stationary* condition, participants only entered their opinion on their assigned robot in their hand. The same steps to enter an opinion mentioned above for the stationary condition happened for the moving condition as well, except that the participants would enter the arena, and the robots would start moving randomly. To enter an opinion, a user had to click on a screen of a moving robot to stop it. After a participant entered their opinion, the robot would start moving randomly, showing the opinion entered last. The robot would stop moving again only if a participant clicked on the screen to enter their opinion.

If within 10 minutes the participants do not reach consensus, the experiment was stopped. Then, the experimental condition was switched to its alternative - therefore, participants were asked to either pick up or put down the Tiles. The second question was introduced for the new experimental condition. Then, we explained what that question would be, and briefed the participants about the second condition, and gave them 10 minutes again to reach consensus.

After participants finished both conditions, they were asked to fill a post-study questionnaire that asked for their participant number, their age, gender, how long they had lived in the country and in the city and their familiarity with robots. Additionally, the participants were asked questions (found in Table I) relating to their experience in the study twice: once for the *stationary* condition and once for the *moving* condition. The choices were based on a Likert scale as follows: Completely Disagree, Disagree, Undecided, Agree, Completely Agree. The whole experiment took about 40

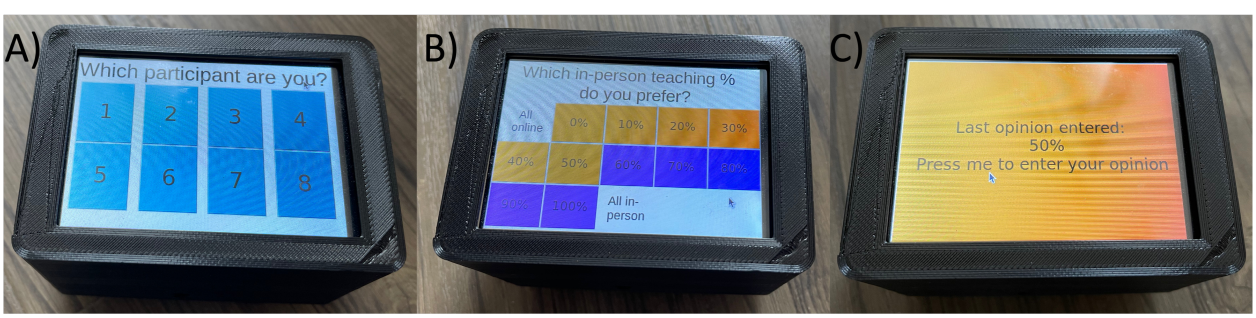

Fig. 2. A) Screen showing the participant number options for the participant to choose their randomly pre-assigned number from. B) Screen showing the question and options given to the participant. C) Screen showing the last opinion entered after the participant has chosen their opinion.

TABLE I

QUESTIONS FROM THE POST-STUDY QUESTIONNAIRE

Questions
1) Interacting with the robots was easy.
2) I was comfortable sharing my opinion using the robots.
3) I felt that I was expressing my opinion anonymously.
4) I had a meaningful impact on the group decision.
5) Seeing my opinion on the robot helped me make a decision.
6) Seeing others' opinions on the robots had an impact on my own decision-making.

minutes (20 minutes for both conditions, 5 minutes briefing and 15 minutes filling questionnaires).

Questions 1 and 2 were focused on the robot interaction, which helped determine whether the hardware of the robot itself affected the experience of the participants, to help test hypothesis 1. The rest of the questions helped decide how the participants felt about the impact and the experience they had while sharing their opinion with the group, which helped test hypothesis 2. Lastly, the participants were asked to write any feedback they have for us.

V. RESULTS

In this section, we present the results obtained during the study.

A. Study experience

In this subsection, we present results from the post-study questionnaire data (see Fig. 3). As mentioned, we had a total of 46 participants in our user study. However, due to an error with the post-study questionnaire given to the first 2 groups, we consider here the data from 31 participants only (the rest of the 4 groups). The mean (μ) and standard deviation (σ) are reported on a scale from 1-5, which correspond to the Likert scale used. For example, 1 represents "Completely Disagree" and 5 represents "Completely Agree". For data analysis, we use either a t-test for data that follow a normal distribution, or a Wilcoxon test for data that follow a non-normal distribution [31], [32].

For "Interacting with the robots was easy", and for the stationary condition, all participants answered either "Completely Agree" or "Agree", with only 2 participants answering "Undecided" (μ=4.29, σ=0.59). As for the moving

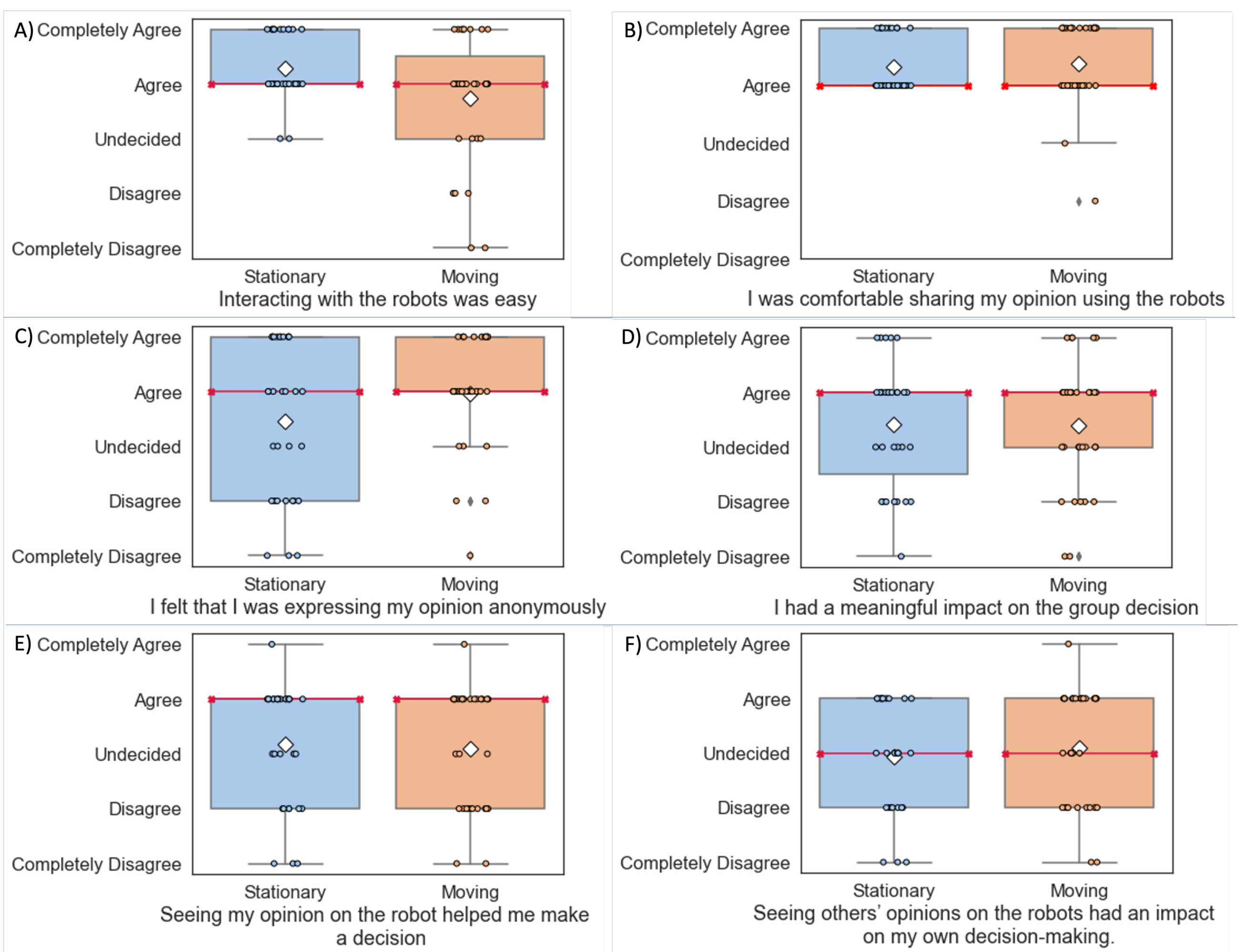

Fig. 3. A)-F) Boxplot figures for the post-study questionnaire questions given to 31 participants. The dots represent the participants' answers, the red line ending with crosses is the median of the participants' answers, and the white diamond is the mean of the answers.

condition, the opinions were more spread (μ=3.74, σ=1.15). This is shown in Fig. 3A. We ran a t-test on both responses and it shows a statistical significance (p=0.0045, effect size=0.599).

In regards to "I was comfortable sharing my opinion using the robots", all participants in the stationary condition responded with either "Agree" or "Completely Agree" (μ=4.32, σ=0.48). As for the moving condition, almost all participants responded with either "Agree" or "Completely Agree", apart from one participant choosing "Disagree" and another choosing "Undecided" (μ=4.38, σ=0.72). This is shown in Fig. 3B. A t-test was run on both responses but there were no statistically significant differences between the two conditions.

For "I felt that I was expressing my opinion anonymously", the answers were slightly more spread out in the stationary condition (μ=3.45, σ=1.41) than the moving condition (μ=3.97, σ=0.98). This is shown in Fig. 3C. A Wilcoxon test was run on both responses and it showed a statistical significance (p=0.019).

For "I had a meaningful impact on the group decision", the answers were spread out in both the stationary condition (μ=3.42, σ=1.12) and the moving condition (μ=3.39, σ=1.15). This is shown in Fig. 3D. A t-test was run on both responses but there were no statistically significant differences between the two conditions.

As for "Seeing my opinion on the robot helped me make a decision", the answers were also similar between the stationary condition (μ=3.17, σ=1.12) and the moving condition (μ=3.10, σ=1.11), as shown in Fig. 3E. A Wilcoxon test was run on both responses but there were no statistically significant differences between the two conditions.

Finally, "Seeing others" opinions on the robot had an impact on my decision-making" had similar answers for the stationary condition (μ=2.93, σ=1.03) and the moving condition (μ=3.10, σ=1.08), as shown in Fig. 3F. A Wilcoxon test was run on both responses and it showed a statistical significance (p = 0.034).

As can be seen from Fig. 3B, almost all participants agreed that they were comfortable using the robots (this would include the participants who were introverts as well as those who were extroverts, which were personality types obtained from the pre-study questionnaire). Otherwise, there were no significant correlations between different personalities and different results with the post-study questionnaire.

B. Individual behaviour

In this subsection, we present the data that was obtained from the robots during the study. This considers the data from all 46 participants (all 6 groups).

We have extracted the number of times participants interacted with the robots. We found that there was a significant increase (p=0.048, effect size=0.41) between the stationary condition (μ=2.54, σ=1.28) and the moving condition (μ=3.30, σ=2.33). This is shown in Fig. 4.

Moreover, there was a significant increase (p=0.025, effect size=0.482) between the first and last opinion entered by each participant between the stationary condition (μ=6.30, σ=11.23) and the moving condition (μ=11.96, σ=12.22). This is shown in Fig. 5.

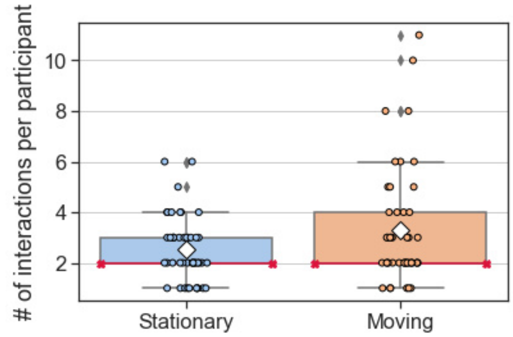

Fig. 4. Boxplot showing the number of interactions for each participant.

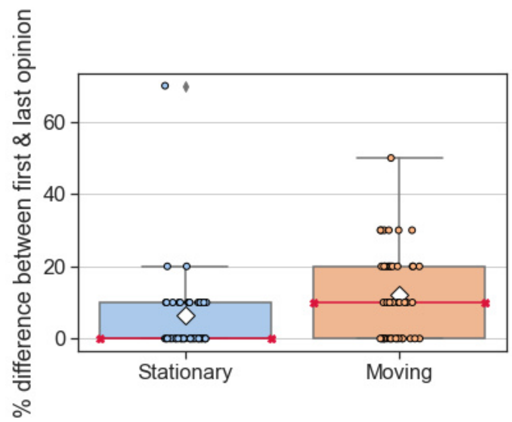

Fig. 5. Boxplot showing the percentage difference between the first and last opinions of each participant.

C. Group behaviour

In this subsection, we present highlights related to the overall group behaviour from all 6 groups.

Different behaviours were observed with different groups. For example, some groups were more talkative than others, and some groups interacted more with the robots than others. The individual opinions can be seen from the graphs on Fig. 6, represented as dots, with time progressing along the x-axis and opinions across the y-axis. The graphs also show a general decrease in the span (diversity) of opinions as the experiment proceeds - most groups have a broad spread of opinions to begin with and then there is a movement towards consensus.

VI. Discussion

It is safe to assume that participants had no major issues when it came to robot interaction for the stationary condition. We suspect that the reason behind the shift of opinion regarding the ease of interaction in the moving condition is caused by the fact that participants had to bend down, stop a robot by pressing on it, then enter their opinion (as opposed

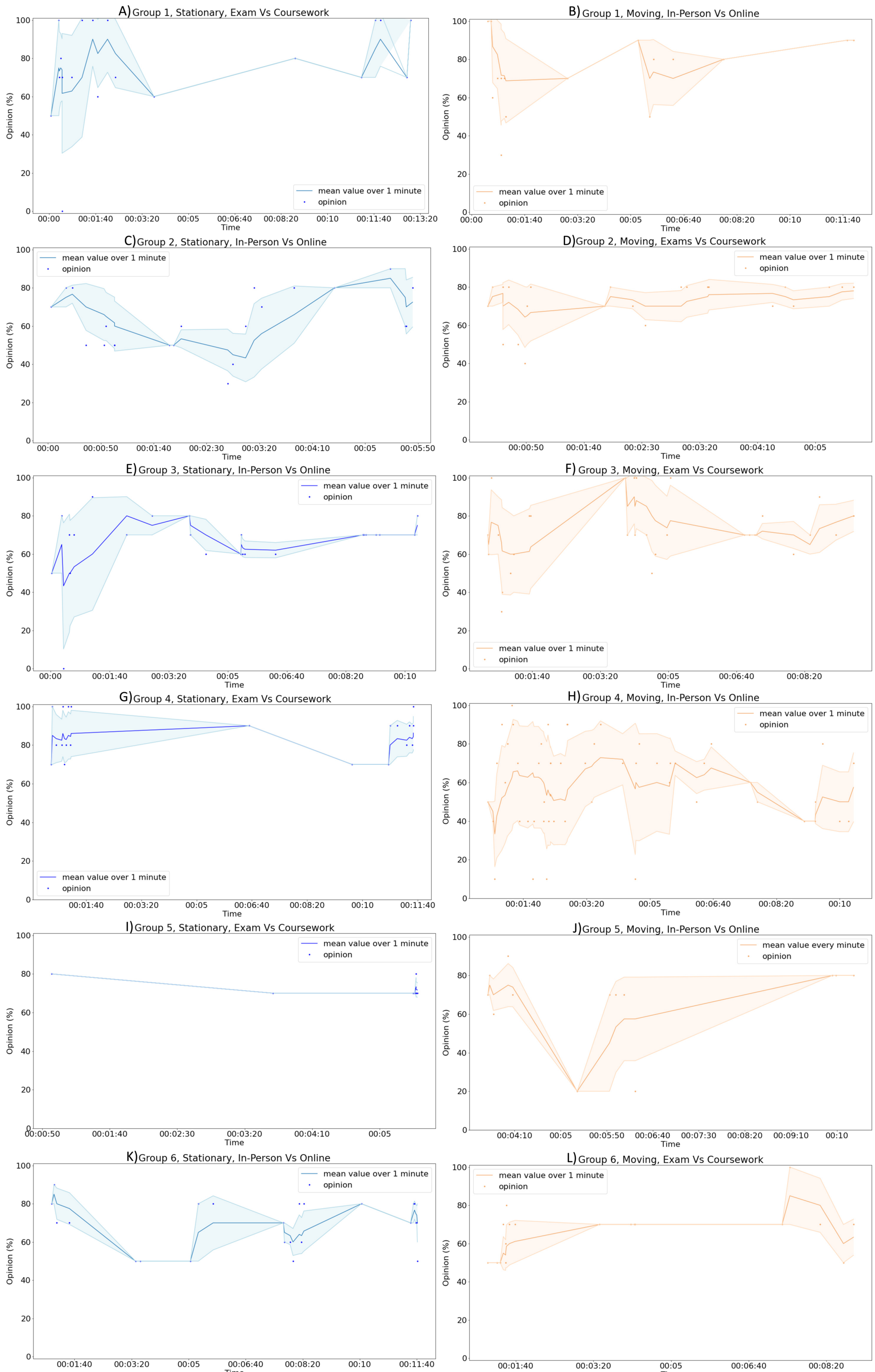

Fig. 6. A)-L) Figures showing opinions during the study. The blue graphs on the left show the stationary conditions for each group, while the orange graphs on the right show the moving conditions for each group. The dots on the graphs represent an opinion entered by a participant. The solid lines on the graphs show the mean taken over the last minute of all opinions entered in that experiment. The shaded regions on the graphs show the standard deviation to that mean.

to just having it ready in their hand all the time). Some participants did mention in the feedback that in the moving condition, “lots of bending over needed” and that “The moving robots may not be convenient for those with mobility impairment”. However, the median was still at “Agree” and the mean was closer to “Agree” than “Undecided”, as shown in Fig. 3A. Therefore, we can conclude that the robot interaction on average was not difficult. However, exposing accessibility constraints on the system design is itself an interesting outcome of this work.

Moreover, almost all participants (except 2) felt comfortable using the robots to express their opinion, as shown in Fig. 3B. Thus, we can conclude that the first hypothesis was supported - the participants felt comfortable using and expressing their opinions through the robots.

Results show that participants felt more anonymous during the moving condition, as shown in Fig. 3C. This makes sense because once the participant enters their opinion, the robot moves away and mixes with other robots. This makes it hard to track which participant voted with which robot, while in the stationary condition, it is easy to look at another participants’ robots to see what they have voted for. We believe anonymity in general is preferable because this will empower people who do not feel comfortable with being clearly identified with their opinion, and so they will still be able to contribute. Thus, mobility of the swarm may increase democratic inclusiveness.

In general, the post-study questionnaires do not clearly show the impact participants felt they had on the group. For questions regarding impact of participants on the group, or whether they felt seeing their opinion or those of others impacted their decisions, answers were spread out. The average of those answers was approximately at “Undecided”, as shown in Fig. 3D,E,F. However, there was a statistically significant difference between the two conditions for “Seeing others’ opinions on the robots had an impact on my own decision making”, with a very small positive increase towards “Agree” in the mean for the moving condition. One participant mentioned in the feedback, “Couldn’t see [other’s opinions in the condition where they were holding the robots] so couldn’t influence [my own opinion]”. However, participants could have walked over to others during the stationary condition to see the opinion entered on the other participant’s robot, if they wished to do so. Participants showed a bigger difference between their first and last opinion (whether higher or lower in percentage) during the moving condition. Also, participants tended to interact more with the robots during the moving condition. This might mean they felt more compelled to voice their opinion. This might be due to the fact that the conversation, as well as seeing other people’s opinions, were factors in helping participants change their minds. As one participant mentioned in the feedback “seeing other opinions on the moving robot made me want to input mine more frequently”. These results then support our second hypothesis, where the movement of the robots does have an impact on user engagement and decision-making process. We have observed in general that the robots did trigger a discussion among members, as one participant wrote in the feedback “was a good tool for triggering discussions even if we didn’t have consensus”.

That being said, it is worth noting that the dynamics of the decision-making process were different for different groups and participants. Most groups start broad in the opinions entered and then converge, as can be seen in Fig. 6A,B,D,E,F,G,H,J. Many also show the mean of the opinion changing from the start to end, examples include those in Fig. 6C,H,J. However, some groups tended to interact more frequently with the robots, examples include those in Fig. 6G,H, while other groups interacted less, as shown in Fig. 6I,J. Therefore, the dynamics of the groups differed from one group to the other, which is expected of human groups who constitute individuals of different personalities and backgrounds.

In the future, we plan to recruit participants outside the robotics community, allowing for more gender diversity in participants as well as lower familiarity levels with robots and robotics. However, we have done outreach activities with members of the public of diverse backgrounds, genders and ages where people used the robots for various tasks such as opinion-mixing and education [3]. People generally found it easy and engaging to use the robots. Moreover, as COVID-19 restrictions are easing, it would be interesting to see how increasing the number of members of the group affects the study. We speculate that if the number of members increases, as well as the size of the space they are in increases, the robot movement will be crucial in communicating opinions. This is because the opinions of participants will mix together and travel via the robots, perhaps to participants who may not have talked to each other during the decision-making process. Some of our participants also had this suggestion as one participant wrote in the feedback: “this interaction is very interesting, if there is more people, the data might be more accurate”.

Moreover, creating decentralised consensus algorithms that use the local interactions between the Tiles to calculate measures such as average opinion or other trends could be explored. This information could be shown to the users during the experiment using the robots. This could be done to help inform participants about trends, to see whether this has an effect on the convergence of opinions.

VII. Conclusion

Group decisions are prominent in everyday life. It is important that the decision-making process be inclusive and open for discussion by members of the group. In this work, we aimed to explore whether a swarm of robots can help a group of human participants in decision-making, by visually communicating opinions of other participants. The swarm of robots we use is called MOSAIX, a swarm that we designed and built. The individual robots are called Tiles, and are 4-inch touchscreens-on-wheels.

We recruited 46 participants into groups of 7 and 8 to test this. We had 2 experimental conditions; *stationary* condition and *moving* condition. In the stationary condition, participants were asked to enter their opinion on a topic while holding a robot as if it were a smartphone. In the moving condition, participants were asked to enter their opinion on another topic while the robots where moving around randomly, showing opinions of other participants. The movement of the robots acted as physical avatars of participants' opinions, allowing opinions to travel and mix together. The participants mostly thought the interaction with the robots was easy, and were comfortable sharing their opinions on the robots. In the moving condition, the participants felt more anonymous, interacted more with the robots, and showed a bigger difference between their first and last opinion. Overall, the robots engaged participants on topics such as online teaching and modules structure, served as a prompt to launch conversations between participants, and empowered participants to share their opinions through physical avatars.

Future work includes experimenting with different group sizes in bigger spaces to see the impact of size on decision-making via the robots. Moreover, we plan to recruit participants outside the robotics community in order to diversify our participant pool. Finally, creating algorithms that enable the robots to calculate and show different trends or measures to the users can be explored to see their effect on opinion convergence.

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