Sharing the Control of Robot Swarms Among Multiple Human Operators: A User Study (Supplementary Material)

Genki Miyauchi[1], Yuri K. Lopes[2], Roderich Groß[1]

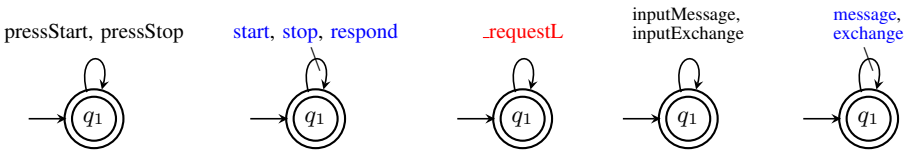
This supplementary material contains the SCT models used by the robots or agents in the experiment as well as the questionnaires provided to the participants during the user study.

I. SCT MODELS

Here, we report the SCT models used by the leader agents and workers for the experiments. The models presented here are based on the models in our previous work:

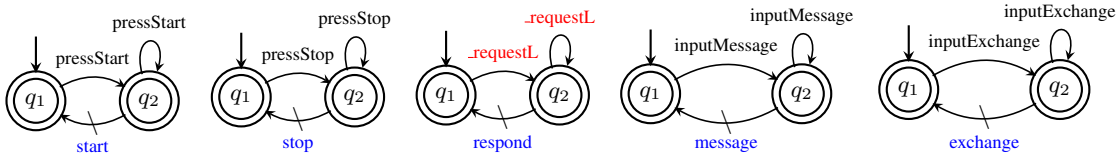
G. Miyauchi, Y. K. Lopes, and R. Groß, "Multi-operator control of connectivity-preserving robot swarms using supervisory control theory," in *2022 IEEE International Conference on Robotics and Automation (ICRA)*, 2022, pp. 6889–6895.

Fig. 1 and 2 show the leader agent's free behavior models and specifications, respectively. Fig. 3 and 4 show the worker's free behavior models and specifications, respectively. Table I summarizes all events that appear in the free behavior models and control specifications. After synchronization using local modular synthesis, the local modular supervisors of leader agents have a total of 10 states and 39 transitions (sum of 5 supervisors), whereas the workers have 154 states and 762 transitions (sum of 10 supervisors).



(a) G_1^L (b) G_2^L (c) G_3^L (d) G_4^L (e) G_5^L

Fig. 1. Free behavior models for the leader agents representing their ability (a) to receive control inputs from the operator, (b) to send messages to the workers, (c) to receive messages from them, (d) to receive inputs from the operator in the form of messages intended for the other operator, or a signal to make a worker switch its team, (e) and to send a message that needs to be relayed to the other lead agent or inform a worker to join the other team. States are represented by circles. The initial state is indicated by an unlabeled arrow. Marked states are represented by double-line circles. Transitions and associated events are shown as labeled arrows. Arrows with a stroke relate to controllable events, and arrows without a stroke relate to uncontrollable events. Public controllable events and public uncontrollable events are shown in blue and red respectively. Controllable events are those that the robots can trigger. Uncontrollable events are those that the robots can only respond to. Public controllable events and public uncontrollable events allows, respectively, for formally modeling the transmission and receiving of communication among robots. Initial states indicate the starting point of the system, while marked states indicates states that the system must always be able to achieve (avoiding blocking).



(a) E_1^L (b) E_2^L (c) E_3^L (d) E_4^L (e) E_5^L

Fig. 2. Control specification for the leader agents allowing them (a–b) to transmit a signal upon receiving the corresponding operator input, (c) to send a response when a request from a follower to become a connector is received, and (d–e) to transmit a signal upon receiving the corresponding operator input.

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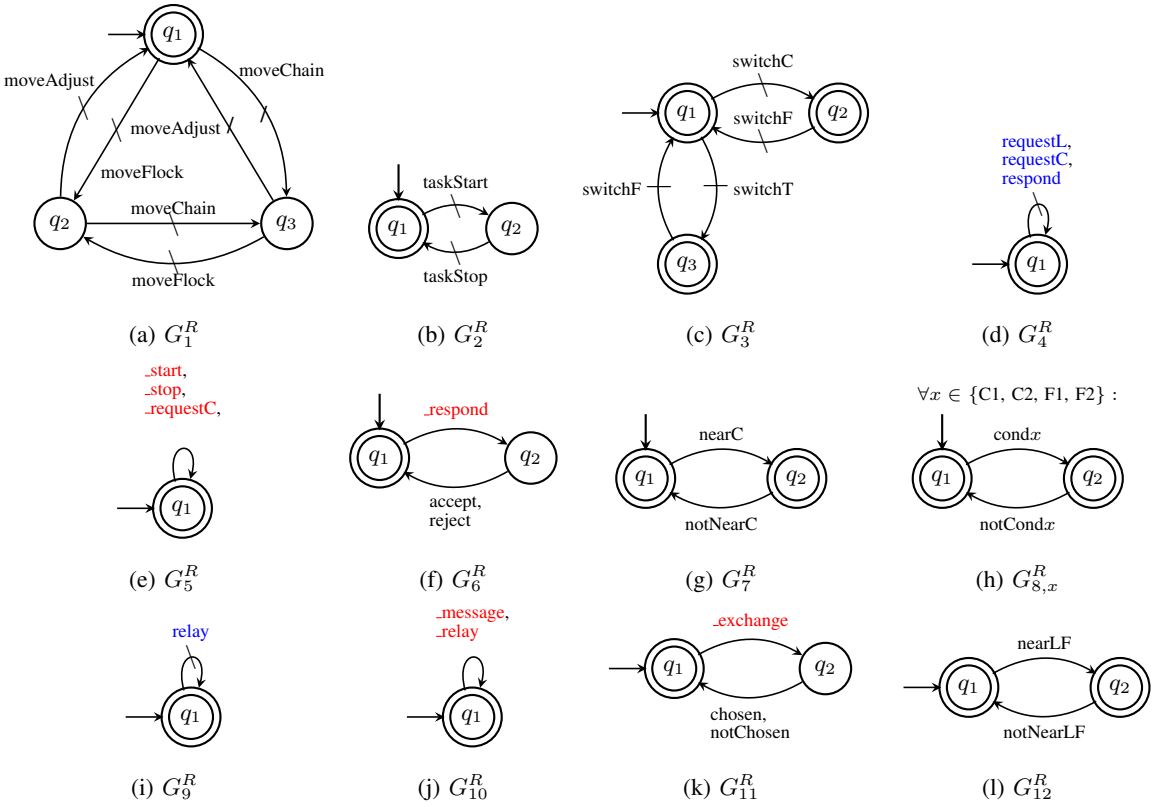
[2] Y. K. Lopes is with Department of Computer Science, Santa Catarina State University, Joinville, Brazil yuri.lopes@udesc.br

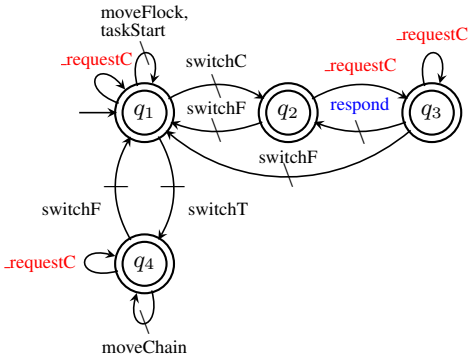


(a) G_1^R (b) G_2^R (c) G_3^R (d) G_4^R

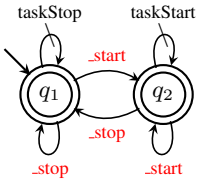
(e) G_5^R (f) G_6^R (g) G_7^R (h) $G_{8,x}^R$

(i) G_9^R (j) G_{10}^R (k) G_{11}^R (l) G_{12}^R

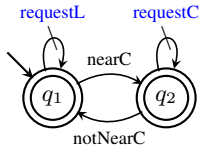
Fig. 3. Free behavior models for the workers representing their ability (a) to either flock, move along the chain, or adjust its position in the chain, (b) to work on a task at their current location, (c) to switch between the follower, connector, and traveler roles, (d–e) to transmit and receive messages related to the execution of tasks and maintaining the robot chain, (f) to process whether it has been chosen to join the chain, (g) to detect nearby connectors, and (h) to determine whether the conditions $C1, C2, F1, F2$ are satisfied, (i) to process whether it has been chosen to move to the other team, and (j) to detect nearby team members.



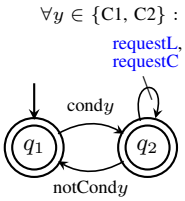
(a) E_1^R



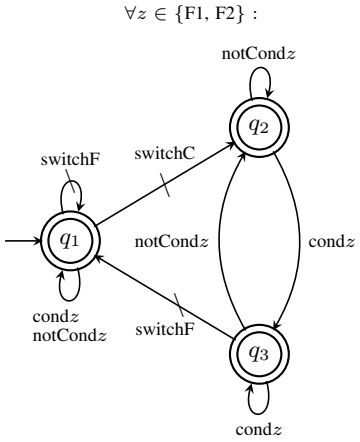
(b) E_2^R



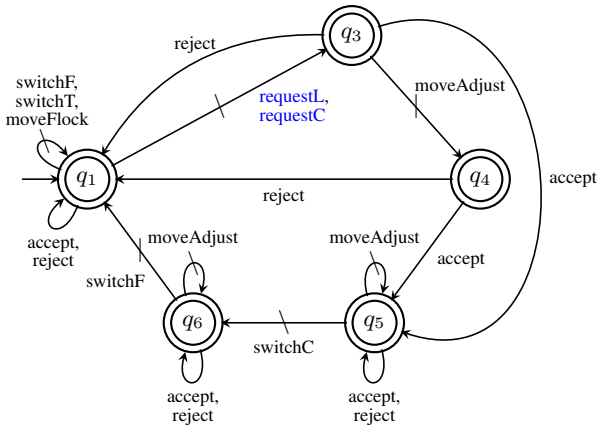
(c) E_3^R



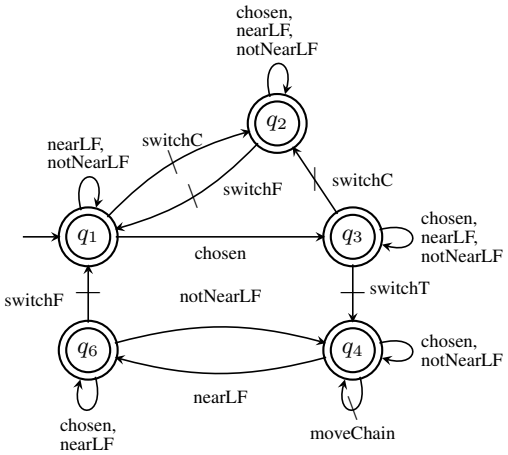
(d) $E_{4,y}^R$



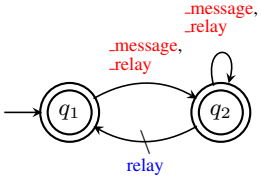
(e) $E_{5,z}^R$



(f) E_6^R



(g) E_7^R



(h) E_8^R

Fig. 4. Control specifications for worker robots allowing them (a) to perform certain actions depending on their role, as a follower, to work on tasks and flock with the leader, as a connector, to send a response when a request from a follower to become a connector is received, as a traveler, to move along the chain to the other team, (b) to start or stop performing tasks when the corresponding signals are received by the leader agent, (c) to determine whom request messages should be sent to, (d) to send request messages for becoming connectors when the conditions are satisfied, (e) to switch from a connector to a follower when the conditions are satisfied, (f) to become a connector when the received response was accepting it to switch roles, (g) to become a traveler when it was chosen by the leader agent, and (h) to relay operator messages it received.

TABLE I

SUMMARY OF EVENTS' DESCRIPTION USED IN THE MODELS (FREE BEHAVIOR MODELS AND CONTROL SPECIFICATIONS). CONTROLLABLE, UNCONTROLLABLE, PUBLIC CONTROLLABLE AND PUBLIC UNCONTROLLABLE EVENTS ARE LABELED $\mathcal{C}$, $\mathcal{U}$, $Pub\mathcal{C}$ AND $Pub\mathcal{U}$ RESPECTIVELY.

Event	Type	Description
moveFlock	$\mathcal{C}$	Robot flocks with the leader.
moveChain	$\mathcal{C}$	Robot moves along the chain to the other team.
moveAdjust	$\mathcal{C}$	Robot adjusts its position in the chain.
taskStart, taskStop	$\mathcal{C}$	Robot starts or stops working on a task.
switchC, switchF, switchT	$\mathcal{C}$	Robot switches to the connector, follower, or traveler role.
pressStart, pressStop, inputMessage, inputExchange	$\mathcal{U}$	Robot detects an operator input.
start, stop	$Pub\mathcal{C}$	Robot sends a signal to start or stop working on a task.
_start, _stop	$Pub\mathcal{U}$	Robot received a signal from the lead agent to start or stop working on a task.
requestL, requestC	$Pub\mathcal{C}$	Robot send a request message to the lead agent or the connector.
_requestL, _requestC	$Pub\mathcal{U}$	Robot received a request from a worker.
respond	$Pub\mathcal{C}$	Robot sends a reply to the request received.
_respond	$Pub\mathcal{U}$	Robot received a response to the request it made to switch to a connector.
accept, reject	$\mathcal{U}$	Process the response to determine whether its request to switch to a connector was accepted or rejected.
nearC, notNearC	$\mathcal{U}$	Robot determines whether a connector was detected or not.
cond$x$, notCond$x$	$\mathcal{U}$	Robot determines whether condition $x \in \{C1, C2, F1, F2\}$ was satisfied or not.
message	$Pub\mathcal{C}$	Robot sends a message to the other lead agent.
relay	$Pub\mathcal{C}$	Robot relays a message to the target lead agent.
_message, _relay	$Pub\mathcal{U}$	Robot received a message that needs to be relayed.
exchange	$Pub\mathcal{C}$	Robot sends a message that specifies a worker that must join the other team.
_exchange	$Pub\mathcal{U}$	Robot received a message from the lead agent related to team switching.
chosen, notChosen	$\mathcal{U}$	Process the message to determine whether it has been chosen to switch to the other team.
nearLF, notNearLF	$\mathcal{U}$	Robot determines whether a team member was detected or not.

II. QUESTIONNAIRES

The participants each completed three questionnaires during the experiment.

The *Preliminary Questionnaire* (1 page) asked about the participant's background and any previous gaming experiences.

The *Post-Trial Questionnaire (1)* (2 pages), and *Post-trial Questionnaire (2)* (3 pages) asked the participants to rate their experience upon completing each trial. After the second trial, the participants were also asked to answer additional questions related to the overall experience (found on the last page of Post-trial Questionnaire (2)).

Preliminary Questionnaire

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Participant ID: ☐

Instruction: Mark your answer.

1. What is your age?

   ☐ Under 20 ☐ 40-49 ☐ Prefer not to say

   ☐ 20-29 ☐ 50-59

   ☐ 30-39 ☐ 60 & over

2. To which gender identity do you most identify?

   ☐ Male ☐ Self-describe: _____

   ☐ Female ☐ Prefer not to say

3. How often do you play video games (including console, PC, mobile)?

   ☐ I play on a daily basis

   ☐ I play a few times a week

   ☐ I play a few times a month

   ☐ I don't play video games regularly but I used to play regularly in the past

   ☐ I don't play video games regularly and I have not played regularly in the past

4. If you play or used to play video games, what is your favourite genre? Please select all that apply.

   ☐ Action ☐ Role-playing game ☐ Puzzle

   ☐ Shooter ☐ Simulation ☐ Rhythm

   ☐ Fighting ☐ Strategy ☐ Other: _____

   ☐ Sports / Racing ☐ MOBA

Post-Trial Questionnaire (1)

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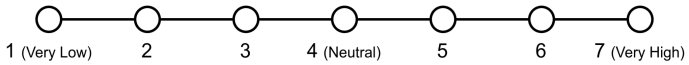
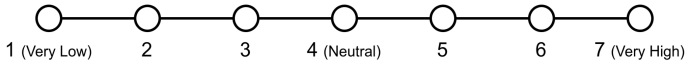
Participant ID: _____

Instruction: Mark one answer.

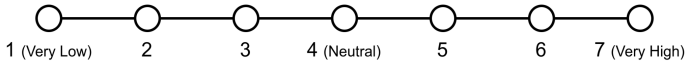
1. **Mental Demand:** How mentally demanding was the task?



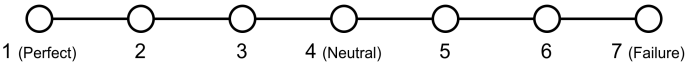
2. **Physical Demand:** How physically demanding was the task?



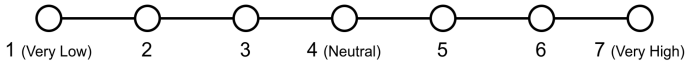
3. **Temporal Demand:** How hurried or rushed was the pace of the task?



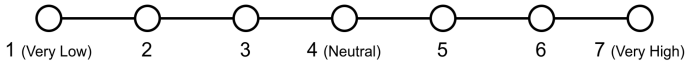
4. **Performance:** How successful were you in accomplishing what you were asked to do?



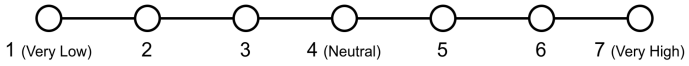
5. **Effort:** How hard did you have to work to accomplish your level of performance?



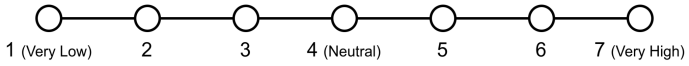
6. **Frustration:** How insecure, discouraged, irritated, stressed, and annoyed were you?



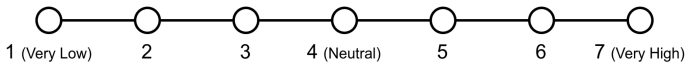
7. **Instability of Situation:** How changeable is the situation? Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?



8. **Complexity of Situation:** How complicated is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?



9. **Variability of Situation:** How many variables are changing within the situation? Are there a large number of factors varying (High) or are there very few variables changing (Low)?



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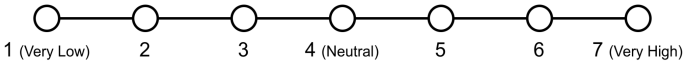
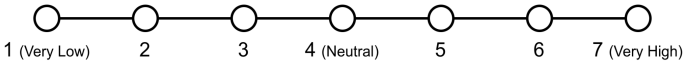
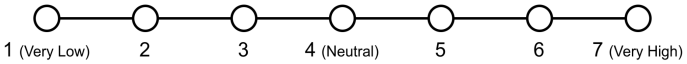
10. **Arousal:** How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?



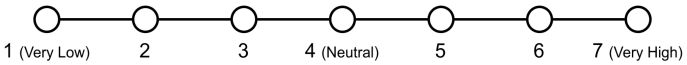
11. **Concentration of Attention:** How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?



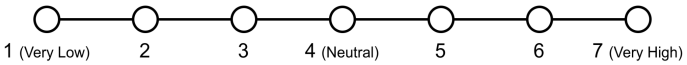
12. **Division of Attention:** How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?



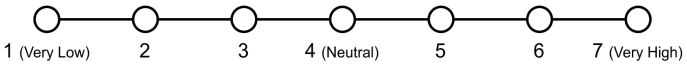
13. **Spare Mental Capacity:** How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?



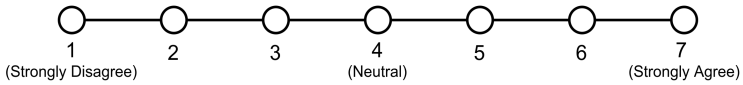
14. **Information Quantity:** How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?



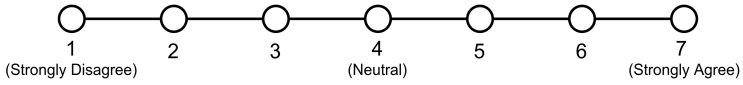
15. **Familiarity with Situation:** How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?



16. Did you understand what your **teammate was doing** at any particular time? Were you able to understand why your teammate was taking a certain action?



17. Did you understand what the **robots were doing** at any particular time? Were you sure how and why the robots were behaving the way they did?



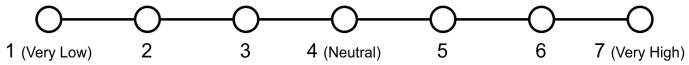
Post-Trial Questionnaire (2)

Sharing the Control of Robot Swarms User Study

Participant ID: _____

Instruction: Mark one answer.

1. **Mental Demand:** How mentally demanding was the task?



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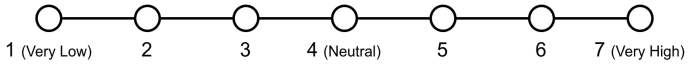
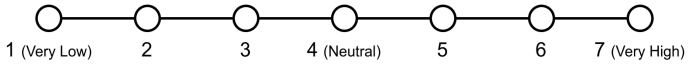
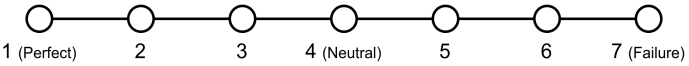


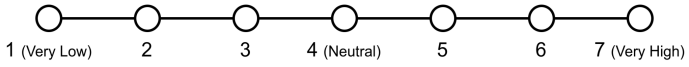
3. **Temporal Demand:** How hurried or rushed was the pace of the task?



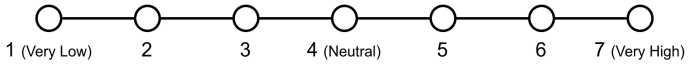
4. **Performance:** How successful were you in accomplishing what you were asked to do?



5. **Effort:** How hard did you have to work to accomplish your level of performance?



6. **Frustration:** How insecure, discouraged, irritated, stressed, and annoyed were you?



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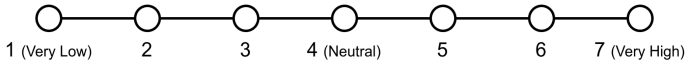

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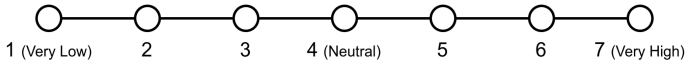

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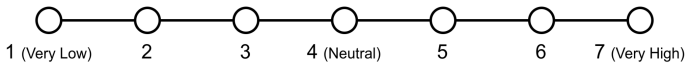

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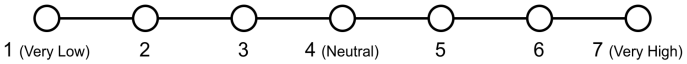
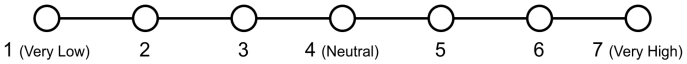
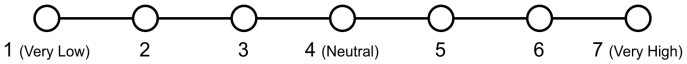
10. **Arousal:** How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?



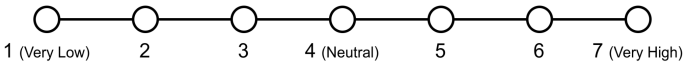
11. **Concentration of Attention:** How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?



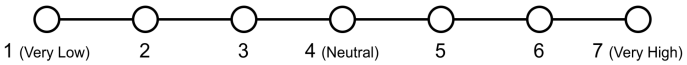
12. **Division of Attention:** How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?



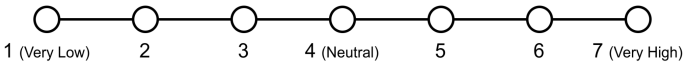
13. **Spare Mental Capacity:** How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?



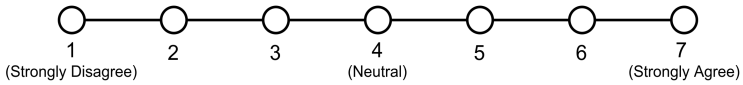
14. **Information Quantity:** How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?



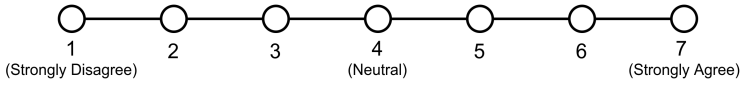
15. **Familiarity with Situation:** How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?



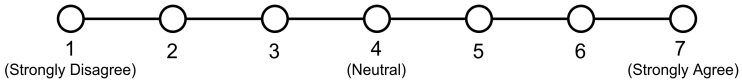
16. Did you understand what your **teammate was doing** at any particular time? Were you able to understand why your teammate was taking a certain action?



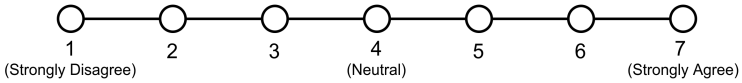
17. Did you understand what the **robots were doing** at any particular time? Were you sure how and why the robots were behaving the way they did?



18. Was the information provided by the interface **clear to understand**?



19. Did you find the **ability to share robots** with your teammate useful in completing the tasks?



20. What was your **strategy** for completing the tasks? Was there anything in particular that you paid attention to during the trial?

21. If you have any additional comments, please write them here.

Thank you for taking part in the study!