Human Responses to Stimuli Produced by Robot Swarms - The Effect of the Reality-Gap on Psychological State

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We study the reality-gap effect (the effect of the inherent discrepancy between simulation and reality) on the human psychophysiological state, workload and reaction time in the context of a human-swarm interaction scenario. In our experiments, 37 participants perform a supervision task (i.e., the participants have to respond to visual stimuli produced by a robot swarm) with a real robot swarm and with simulated robot swarms. Our results show that the reality-gap significantly affects the human psychophysiological state, workload and reaction time. Our results also show that conducting a human-swarm interaction experiment in a virtual reality environment can be an alternative to conducting an experiment with robot swarms simulated on a computer screen. These results suggest that virtual reality can mitigate the effect of the reality-gap in human-swarm interaction experiments.

1 Introduction

There are fundamental differences between the way a human interacts with a robot swarm and the way a human interacts with a single robot. Firstly, because robots in a swarm robotics system do not have the same communication capabilities as most of the other robotics systems (e.g., text-based or voice-based communication hardware). Secondly, because even if they were augmented with communication ca-

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pabilities, the large number of robots that compose a swarm robotics system would make it impractical for a human operator to interact with each individual robot—there would be too many data-points for the human operator to process.

Because of these fundamental differences, human-swarm interaction (HSI) has become an active and independent field of research. In the current HSI literature, most research tackles technical aspects of the interaction (e.g., gesture-based interaction, speech-based interaction, haptic-based interaction, leader-based robot swarm control) and only few researches are validated with user studies (see [8] for a comprehensive survey of HSI). Moreover, with the exception of [19] and [17], the majority of these user studies are performed in simulation only [2, 13, 3, 23, 7, 22, 14, 12]. Though simulation is convenient for the repeatability of the experiments and for the low-cost of the infrastructure (i.e., robots and experimental room), simulation suffers from the so-called *reality-gap*—the inherent discrepancy between simulation and reality.

These user studies, performed in simulation only, have motivated us to investigate the effect of the reality-gap in the context of HSI. We are interested in understanding whether the reality-gap affects the psychology of humans interacting with a robot swarm. For instance, do human operators feel more stressed or overloaded when they interact with a real robot swarm than with a simulated robot swarm displayed on a computer screen (which is used in the majority of the human-swarm interaction user studies)? In [16], we have already shown that the reality-gap had an effect on the human psychophysiological state (i.e., the psychological state of a human assessed by physiological measures) when humans are passively interacting with a robot swarm. In this paper, we also study the effect of the reality-gap on the human psychophysiological state, however, our participants are not purely passive anymore. Even though our participants do not issue any commands to the robot swarm (because an interaction interface could influence the psychophysiological responses of the participants, thus limiting the visibility of the reality gap effect [16]), they are asked to press a button each time a robot illuminates its LEDs in red. Thanks to this task, we show in this paper that the reality-gap has also significant impacts on the human workload (i.e., the mental effort) and reaction time. In the experimental scenario designed for our experiments, 37 participants interact with a simulated robot swarm displayed on a computer screen, with a simulated robot swarm displayed in a virtual reality environment and with a real robot swarm. Fig. 1 shows the three experimental scenarios.

This paper contributes to the literature in two ways. The first contribution is that our results show that our participants have stronger psychophysiological reactions and higher workload and reaction time when they interact with a real robot swarm than when they interact with a simulated robot swarm displayed on a computer screen. The second contribution is that we show that our participants' workload and reaction time are higher when they interact with a robot swarm simulated in a virtual reality environment than with a robot swarm simulated on a computer screen. These results suggest that conducting simulation-based experiments in a virtual reality environment can mitigate the effect of the reality-gap in HSI and, therefore, HSI researchers can avoid to buy and maintain expensive real robots.

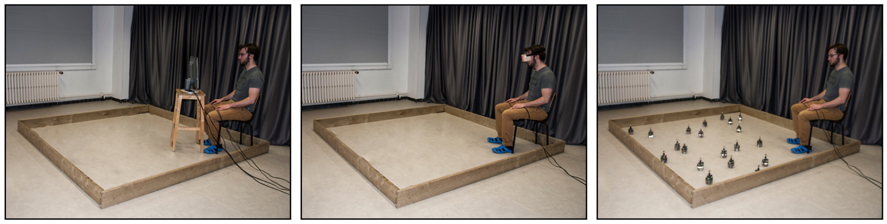

Fig. 1: Experimental scenario. *Left:* A participant interacts with a simulated swarm of 20 robots displayed on a computer screen. *Middle:* A participant is attached to a virtual reality head set and interacts with a simulated swarm of 20 robots. *Right:* A participant interacts with a swarm consisting of 20 real robots. The participant shown in this figure is the first author of this paper and did not take part in the experiment. The pictures shown in this figure were taken for illustration purpose.

2 Related Literature

The effect of the reality-gap on the human psychology has been studied in human-robot interaction, and more specifically, in the context of social robotics. In social robotics, the majority of the studies show that human beings enjoy more to interact with a real robot than with a simulated one [6, 21, 18, 15, 10, 4, 24]. In these studies, the authors measured the level of enjoyment either with a self-developed questionnaire or with the game flow model—a model initially developed to measure the players enjoyment in games [20]. In HSI, though, we were the first to study the effect of the reality-gap on the human psychology [16]. We showed that due to the reality-gap, humans had stronger psychophysiological responses when they passively interacted with a real robot swarm than with a simulated robot swarm.

In HSI research, several studies had already taken into account the human psychology during the interaction with a robot swarm. In [14], the authors showed that the human workload (assessed by a subjective questionnaire) is not affected by the size of a robot swarm (i.e., the number of robots in a swarm). In [17], however, we showed that the size of a robot swarm has a significant effect on the human psychophysiological state. In this research, we studied the psychophysiological state with a combination of objective physiological measures (skin conductance and heart rate) and subjective psychological measures (via a questionnaire). The effect of two types of command propagation methods (i.e., methods to disseminate a human command among the robots of a swarm) was studied in an experiment where a human operator had to guide a swarm of robots by controlling a leader robot's velocity and heading [22, 1]. The authors showed that workload is lower with the so-called flooding method (non-leader robots all set their velocity and heading to those of the leader robot) than with the so-called consensus method (non-leader robots set their velocity and heading to the average velocity and heading of their neighbours). Workload can also be affected by different types of communication network topologies made by the robots [3]. In [19], finally, the authors showed that the mapping between the manipulability of a swarm (i.e., whether it is easy or hard to guide a robot swarm) and haptic forces also impacts the human workload. With the exception of [19] and [17], all the aforementioned studies were performed in simulation. Because of the reality-gap, though, it is difficult to confirm that these results would be similar if the experiments were conducted with a real robot swarm instead of a simulated one.

This paper is different from [16] for two reasons. Firstly, because our participants are not purely passive during the interaction with a robot swarm. Secondly, because in addition to studying the reality-gap effect on the human psychophysiological state, we also study its effect on the human workload and reaction time, providing a more complete understanding of the reality-gap effect in HSI.

3 Methodology

3.1 Hypotheses

We based the experiment presented in this paper on two hypotheses:

1. The psychophysiological reactions, workload and reaction time of humans are higher when they interact with a real robot swarm than with a simulated one.
2. The psychophysiological reactions, workload and reaction time of humans are higher when they interact with a simulated robot swarm displayed in a virtual reality environment than with a simulated robot swarm displayed on a computer screen.

Confirming the first hypothesis would allow us to show that, not only the reality-gap has an effect on the human psychophysiological state, but equally importantly, that it has also an effect on the human workload and reaction time. Confirming the second hypothesis would suggest that conducting HSI experiments in a virtual reality environment could mitigate the effect of the reality-gap—the way humans would react when interacting with a robot swarm in a virtual reality environment would be more similar to the way they would react with a real robot swarm than to the way they would react with a robot swarm simulated on a computer screen.

In the next section, we present the experimental scenario used to test these two hypotheses.

3.2 Experimental Scenario

In order to test our two hypotheses, we designed an experimental scenario similar to that of [16]. In this experimental scenario, our participants' task is to supervise a swarm consisting of 20 robots for a period of 60 seconds. In this paper, the supervision tasks consists for our participants to watch attentively a robot swarm and press a button each time a robot of the swarm illuminates its LEDs in red.

The experimental scenario is divided into three sessions—the *Screen Simulation* session, the *Virtual Reality* session and the *Real Robots* session. In these sessions, our participants conduct the supervision task with three types of visualization interfaces. In the *Screen Simulation* session, the robot swarm is simulated in 2D and displayed on a computer screen (the participants see the robot swarm from the top view). In the *Virtual Reality* session, the robot swarm is simulated in 3D and displayed in a virtual reality environment (the participants see the robot swarm as they would see it in reality). In the *Real Robots* session, the robot swarm is composed of real robots. We decided to compare a 2D (top-view) simulation with the reality because this is how the majority of the user studies in human-swarm interaction display the robot swarm[1]. We decided to compare a 3D simulation (virtual reality) to the 2D simulation and to reality in order to test our second hypothesis.

The order our participants encounter these 3 sessions is random.

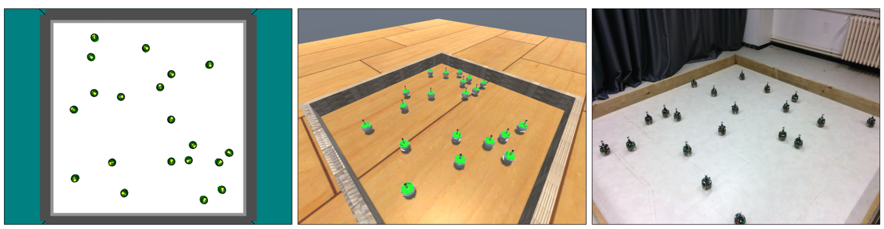

Fig. 2: Robots and environments used in the three sessions. Left: The environment displayed in the *Screen Simulation* session. Middle: The environment displayed in the *Virtual Reality* session. Right: The real environment. The views of these three environments are displayed from the participant's perspective.

3.3 Measures

In this study, we used a combination of subjective measures and objective measures. The subjective measures consist of two questionnaires—the Self-Assessment Manikin (SAM) questionnaire [9] and the NASA Task Load Index Scale (NASA-TLX) questionnaire [5]. We use the SAM questionnaire to study the participants' subjective valence (measure of pleasure-displeasure) and arousal (measure of the mental alertness and physical activity). The SAM questionnaire has 2 scales, each scale being composed of 9 pictures. In a scale, a picture represents a value of that

[1] Please note that this particular choice introduces the question of whether any differences observed between virtual reality and simulation are due to the different perspective. As discussed in the conclusions, this aspect will be considered in future work.

scale (valence or arousal). We use the NASA-TLX questionnaire to study the participants' workload. In the NASA-TLX questionnaire, the workload is divided into 6 scales. In this paper, we use a simpler version of the NASA-TLX questionnaire—the NASA-RTLX, in which the result is the average of the raw score of the six scales. The objective measures consist of the physiological activity and of the reaction time of our participants. We study the physiological activity of our participants by monitoring their heart rate (number of beats per minute) and skin conductance level (slow variation of the skin conductance over time). We collect our participants' reaction time by measuring the time taken by our participants to press a button after a robot illuminates its LEDs in red.

The baseline physiological activity of an individual (i.e., the physiological activity at rest) can be highly different from the baseline of another individual. In order to be able to compare physiological responses across our participants, we monitored our participants' physiological responses at rest and our participants' physiological responses during the experiment. To conduct our analyses, we used the difference between our participants' physiological responses during the experiment and at rest.

3.4 Physiological Data Acquisition and Robot Platform

Physiological measures were acquired by a PowerLab 26T data acquisition system and by a supplementary GSR Amp device connected to the PowerLab 26T system (ADInstruments). A pulse transducer was directly connected to the PowerLab 26T (for monitoring the heart rate) and two finger electrodes were connected to the GSR Amp device (for monitoring the skin conductance level). The PowerLab 26T system was connected to a laptop computer running Mac OSX Yosemite. We used LabChart 8 to collect the physiological data.

The robotic platform used in this study is the e-puck robot platform. The e-puck robot is a robotic platform used for educational purposes [11]. In this study, we only used a subset of the e-puck's sensors and actuators. We used the proximity sensors for obstacle avoidance (i.e., to detect walls and other robots) and the wheel actuators to control the robots' motion (see Sect. 3.5).

3.5 Environment and Robot Behaviour

In our experimental scenario (see Sect. 3.2), we used a 2 m $\times$ 2 m environment, as shown in Fig. 2. The 20 robots used in this experiment are randomly placed in this environment at the beginning of each of the three sessions (i.e., *Screen Simulation*, *Virtual Reality*, *Real Robots*). When a session starts, the 20 robots perform a *random walk with obstacle avoidance* behaviour that lasts 60 seconds. In this behaviour, each robot follows two rules. The first rule is to go straight with a constant velocity of 10 cm/s. The second rule is to change its direction when it encounters either a wall or a robot. In addition to performing a random walk with obstacle avoidance behaviour, each robot illuminates its LEDs in red with a certain probability. The probability is computed by an external software running on the experimenter's computer (there is a TCP communication link between the software and each robot). The software computes this probability as follows. Each 100 milliseconds, with a probability of 0.02, the software randomly chooses a robot's identification number (each robot has a unique identification number). With a probability of 0.98, the software does not choose any robot's identification number. When the software selects an identification number, it sends a signal (i.e., a message via the TCP communication link) to the robot associated to that identification number. When a robot receives a signal, it illuminates its LEDs in red for 2 seconds. When the software chooses an identification number, it also makes sure to wait 2 additional seconds in order to prevent two robots from being illuminated at the same time.

3.6 Participants

For this experiment, we recruited 37 participants. These participants came from the campus population of the Université Libre de Bruxelles (no participant had a robotic background). They were between 17 and 30 years old with an average age of 23.2 years old ($SD = 3.54$). People with current or anterior cardiovascular problems could not participate to the experiment. Our participants had to read and sign an informed consent form explaining that we monitored their physiological activity during the experiment. We offered a 7 € financial incentive for their participation.

3.7 Experimental Procedure

The experiments took place at IRIDIA, the artificial intelligence laboratory of the Université Libre de Bruxelles. We started the experiment by explaining to the participant the supervision task (i.e., watch a swarm of robots attentively and press a button each time a robot in the swarm illuminates its LEDs in red). Then, we showed to the participant the three interfaces used in each session (the simulated robots displayed on a computer screen, the simulated robots displayed in a virtual reality headset and the real robots in the real environment). We allowed the participant to carefully look at the robots in each interface in order to get familiarised with each of them. Once familiarised with the three interfaces, we explained how to answer the SAM and the NASA-RTLX questionnaires. After the participant signed the consent form, we asked the participant to take a seat on a chair placed in a corner of the environment used in the *Real Robots* session. The participant stayed seated on the chair during the whole duration of the three sessions (we placed a computer screen in front of the participant prior to the *Screen Simulation* session and we attached a virtual reality headset to the participant prior to the *Virtual Real-*

ity session). Once seated, we attached the physiological sensors to the participant's non-dominant hand. Prior to the first session, we collected the participant's baseline (i.e., physiological responses at rest) for five minutes. After these five minutes, we proceeded with the first session. After the first session, we administrated the SAM and the NASA-RTLX questionnaires to the participant. We pursued by collecting the participant's baseline for three minutes. This three minute baseline period allowed the participant to calm down and get back to their physiological activity at rest. We followed the same procedure for the second and third session. After the experiment, we explained the goal of the experiment to the participant and we answered their questions. The whole experiment's duration was 30 minutes per participant.

4 Data Analysis and Results

Due to the fact that our participants had to press a button during the experiment, the heart rate data became too noisy to be usefully analysed (the pulse transducer sensor is extremely sensible to small movements). We, therefore, decided not to analyse our participants' heart rate data. Out of the 37 participants, we had to remove the skin conductance data of 6 participants due to sensor misplacement. We also removed the SAM questionnaire data and the NASA-RTLX questionnaire data of 3 participants due to an error of the experimenter in the administration of the questionnaires. We finally removed the reaction time data of 4 participants due to a hardware problem with the button. We performed, therefore, our statistical analyses on 31 skin conductance data (17 female and 14 male), 34 SAM and NASA-RTLX questionnaire data (19 female and 15 male) and on 33 reaction time data (19 female and 14 male). We analysed our data with the R software by performing a repeated measure design analysis. We used the non-parametric Friedman test to determine whether the reality-gap has a significant effect on our participants' measures (i.e., skin conductance, arousal, valence, NASA-TLX and reaction time). In case of statistical significance of the Friedman test, we performed multiple Wilcoxon rank-signed tests with Bonferroni corrections to evaluate the significance of the differences between sessions. In Table 1, we summarise the results by giving the median and the Friedman's mean ranks and the inference statistics of the Friedman tests (i.e., p-values and χ^2).

Skin conductance level – The results of the Friedman test on the skin conductance level show a main effect of the reality-gap on our participants ($\chi^2(2)$ = 14, $p < .001$). A Wilcoxon rank-signed test on the skin conductance level data highlights a statistically significant difference between the *Virtual Reality* session and the *Real Robots* session ($Z = 3.58$, $p < .001$) and between the *Screen Simulation* session and the *Real Robots* session ($Z = 3.68, p < .001$). The Wilcoxon rank-signed test does not show any statistically significant difference between the *Screen Simulation* session and the *Virtual Reality* session ($Z = 0, p = 1$), see Fig. 3.

SAM questionnaire – The Friedman test on the SAM questionnaire data reports a main effect of the reality-gap on our participants' arousal ($\chi^2(2) = 25.35, p <$ .001). It does not show any main effect of the reality-gap on our participants' va-

Table 1: Descriptive statistics of the psychophysiological data, of the self-reported data and of the reaction time data. We report the median and the Friedman's mean rank (in parentheses) of the three sessions (*Screen Simulation*, *Virtual Reality*, *Real Robots*). We also report the inference statistics of the Friedman test (i.e., χ^2 and p value).

Dependent Variable	n	Scree-Simulation	Virtual-Reality	Real-Robots	χ^2	p
SCL	31	1.47 (1.71)	1.93 (1.74)	4.54 (2.54)	$\chi^2(2) = 14$	$<$ **.001**
Arousal	34	3 (1.33)	5 (2.35)	5 (2.31)	$\chi^2(2) = 25.35$	$<$ **.001**
Valence	34	7 (1.9)	7 (1.9)	7 (2.14)	$\chi^2(2) = 1.38$	1
NASA-RTLX	34	18.33 (1.23)	35 (2.47)	27.5 (2.29)	$\chi^2(2) = 32.25$	$<$ **.001**
Reaction Time	33	0.72 (1.39)	1.02 (2.6)	0.87 (2)	$\chi^2(2) = 24.24$	$<$ **.001**

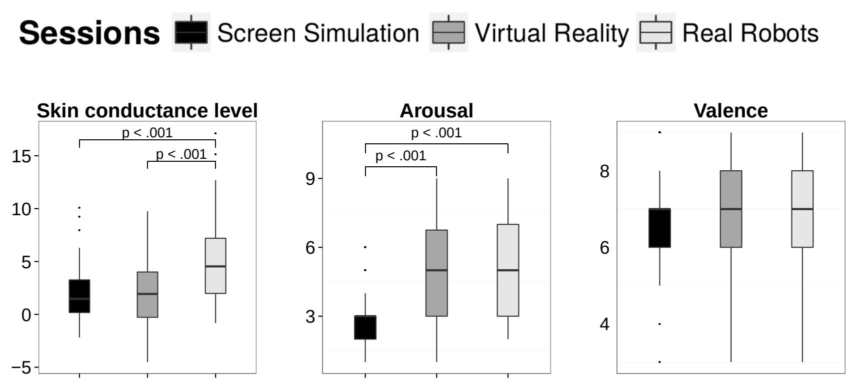

Fig. 3: Boxplots showing the skin conductance level values (left), the arousal values (middle) and the valence values (right) of all three sessions (*Screen Simulation*, *Virtual Reality*, *Real Robots*). The median value of each session is shown using the bold horizontal line in the box. Outliers are represented using dots. We also report the results of the pairwise Wilcoxon rank-signed test by connecting the boxplots of the sessions showing pairwise statistically significant differences.

lence ($\chi^2(2) = 1.38, p = 1$). The Wilcoxon rank-signed test on the arousal data shows that there is a statistically significant difference between the *Screen Simulation* session and the *Real Robots* session ($Z = 4.08, p < .001$), and between the *Screen Simulation* session and the *Virtual Reality* session ($Z = 4.37, p < .001$). The Wilcoxon rank-signed test does not show any statistically significant difference between the *Virtual Reality* session and the *Real Robots* session ($Z = -0.06, p = .9$), see Fig. 3.

NASA-RTLX questionnaire – The results of the Friedman test on our participants' workload (NASA-RTLX) show a main effect of the reality-gap ($\chi^2(2) =$

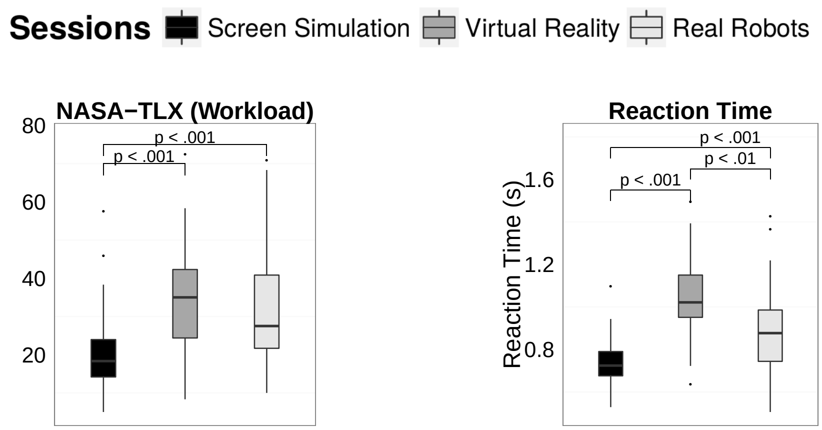

Fig. 4: Boxplots showing the workload level values (left), and the reaction time values (right) of all three sessions (*Screen Simulation*, *Virtual Reality*, *Real Robots*).

$32.25, p < .001$). The Wilcoxon rank-signed test shows a statistically significant difference in the workload level of our participants between the *Screen Simulation* session and the *Real Robots* session ($Z = 4.54, p < .001$) and between the *Screen Simulation* session and the *Virtual Reality* session ($Z = 4.46, p < .001$). There was no statistical difference between the *Virtual Reality* session and the *Real Robots* session ($Z = -0.52, p = .61$), see Fig. 4.

Reaction time – Finally, the results of the Friedman test on our participants' reaction time report a main effect of the reality-gap ($\chi^2(2) = 24.24, p < .001$). The Wilcoxon signed-rank test shows a statistically significant difference between the *Real Robots* session and the *Virtual Reality* session ($Z = -2.84, p < .05$), between the *Screen Simulation* session and the *Real Robots* session ($Z = 3.42, p < .001$) and between the *Screen Simulation* session and the *Virtual Reality* session ($Z = 4.58, p < .001$), see Fig. 4.

5 Discussion and Conclusions

In this paper, we have shown that the reality-gap affects the psychology of humans who perform a supervision task with a robot swarm. More specifically, we have shown that the human psychophysiological state, workload and reaction time measured for the case of interaction with a real robot swarm and for the case of interaction with a simulated robot swarm displayed on a computer screen were significantly different. These results show that it is vital to take into account the reality-gap when researchers design an HSI experiment.

A solution to avoid the reality-gap effect would be to perform HSI experiments with real robots. However, real robot experiments are expensive and time consuming. Therefore, we investigated the possibility to use virtual reality as an alternative to using real robots. Our results show a difference between simulation in a virtual reality environment and simulation on a computer screen—our participants' arousal, workload and reaction time were significantly higher when they were interacting with the robot swarm in the virtual reality environment than when they were interacting with the simulated robot swarm displayed on the computer screen. These results suggest that virtual reality can mitigate the effect of the reality-gap. However, we should qualify these results because our participants' reaction time was also significantly higher when they were interacting with the robot swarm in the virtual reality environment compared to when they were interacting with the real robot swarm. Though these results do not contradict our hypothesis, we believe more research is necessary to better understand the use of virtual reality in HSI studies. In addition, we should account for the possibility that the difference of perspectives (top-view in the 2D *Screen Simulation* session and similar to the reality in the 3D *Virtual Reality* session) has also an effect on the participants' psychophysiological state, workload and reaction time. Future work should investigate whether the difference of perspectives has a significant impact on the human psychophysiological state (e.g., replicating the experiment presented in this paper by replacing the 2D top-view perspective of the *Screen Simulation* session with a 3D perspective of the robots and of the environment).

In the experimental scenario used in this paper, our participants did not issue commands to the robot swarm they interacted with. The reason behind this choice was to isolate the effect of the reality-gap—it would have been difficult to associate higher psychophysiological reactions or higher workload and reaction time to the reality-gap if our participants were, at the same time, requested to issue commands to the robot swarm. This is because the interaction interface might have some effects on our participants as well, making less clear the effect of the reality-gap. Now that we have shown the effect of the reality-gap in an experimental scenario in which human operators do not issue commands to a robot swarm, future work should focus on the effect of the reality-gap in an experimental scenario in which human operators do send commands to a robot swarm (using the results presented in this paper as a baseline).

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