When is human-robot joint agency effective? The case of cooperative reaction games

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Abstract

Here, using a cooperative reaction game, we compared human interaction with an anthropomorphic robot and a computer program. The assistant (either the robot or the program) took over half of the tasks that the participant faced in the game. In half of the game sessions, the assistant reacted slowly, and in the other half, it reacted faster than naive participants. Together with the fast-paced robot, participants scored significantly more points, than with the fast-paced program. This difference was made by the players, as there was no difference in performance between the robot and the program. In addition, human reaction time varied with the pace of the robot, but not the program. We believe that the participants played better with the robot and adopted its pace because they perceived it as a real co-agent. According to the survey, the participants preferred to play with the robot. Together, these results suggest promising prospects for joint human-robot agency and the use of anthropomorphic robots.

Keywords: human-machine interaction, human-robot interaction, joint agency, anthropomorphic robot, reaction task

Statements and Declarations

Conflicts of Interest: The authors declare no conflict of interest.

Data availability statements: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

1. Introduction

1.1 Joint agency in human-robot interaction

People routinely use robotic devices for a variety of tasks. Interactions with robots can be arranged in a number of ways [1], and they are changing with the advancement of technology. Traditionally, robots are used as automatic devices, or as teleoperated devices (e.g. [2]), which implies that a human agent directly controls the robot in detail or specifies its operations in advance. Yet, in many interaction scenarios this degree of control may be unnecessary, requiring inadequate attention or effort. The rapid development of artificial intelligence could greatly expand the field of application of anthropomorphic robots. It is very likely that in a range of scenarios, joint agency [3, 4] with an anthropomorphic robot will prove more efficient and comfortable for us than using a robot solely as a pre-programmed or teleoperated tool. By withdrawing some of the control, a human agent can act together with a robot, cooperating with it, rather than controlling it directly. Such interaction should be safe, predictable and relaxed, not requiring complex deliberation of the robot’s actions by a person [5]. Unlike a tool, a robotic agent would be able to interact with a person based on their emotional state, which could enhance human-robot interaction. Here, we will focus on joint agency in proximate human-robot interaction [6], since remote interaction lacks important visuomotor cues.

Similar to the use of tools, joint agency is a natural and stable type of behavior. During social interactions, people constantly monitor signals from others, and it happens implicitly through the activation of mirror systems [7]. While working together, co-agents suggest their competences and share their responsibilities, which allows them to distribute their cognitive and physical efforts more effectively. They develop a sense of agency for these joint activities [8, 9]. It is possible that joint agency can also arise during human-robot interaction, and hypothetically the probability of its occurrence is higher when anthropomorphic robots are used. In some cases, an anthropomorphic robot can be perceived as another social agent [10]. When interacting with a robot, but not with a simple device, humans experience a decrease in control [11] that is inherent in human-human interaction due to the partial transfer of responsibility. Presumably, the likelihood of attributing agency to a robot depends largely on the individual's preconditioning, their beliefs about how the robot operates [12].

1.2 Social Simon task as an indicator of perceived agency

Establishing a social interaction with a robot is not an easy task, requiring consideration of multiple factors. For example, the way that a robot is perceived can be affected by complex factors such as its gaze direction [13] and other nonverbal behavior [14]. It is important to remember the unsuccessful examples of electronic assistants: although it is nor a robot, the Office Assistant paperclip in Microsoft products famously received a serious backlash [15]. One way of studying whether humans perceive a robotic assistant as an agent is to arrange the social Simon task [16] based on the Simon task [17].

First, let us describe the Simon effect. Suppose a participant is seated in front of a screen and is tasked with responding to visual stimuli. In response to one type of stimulus, they have to press a key under their left hand, and to another type of stimulus - a key under their right hand. The Simon effect is the phenomenon of participants reacting significantly faster to the stimuli presented on the side of the screen that corresponds to the response hand. It is known that the effect disappears if a participant is instructed to respond to only one of the stimuli. However, the effect will reappear if another participant responds to the second stimulus - and this phenomenon is called the social Simon effect. The effect is thought to arise from the co-representation of another agent's movements.

The social Simon effect was also obtained when performing a task together with anthropomorphic robots [18–20]. If a non-anthropomorphic software assistant responds to the second stimulus, no effect is observed [21]. It was also not obtained when participants performed the task with an image of a wooden hand [22] in contrast to an image of a real human hand. However, in a more recent study the effect emerged in a task performed together with a robotic hand [23]. In summary these results indicate that as co-representation of movements of a human hand is more likely to occur, movements of a robotic hand can also be co-represented at least in case of an embodied robot. Thus, the emergence of the social Simon effect may serve as one of the indicators that humans perceive a robot as a co-agent.

1.3 Assessing the effectiveness of interaction

A separate question is how to evaluate the effectiveness of cooperative interaction with robots. It is partly confirmed that most people have a generally positive perception of anthropomorphic robots in various contexts, but the current state of research does not provide sufficient evidence to predict the effectiveness of interaction with them in specific settings [24]. The effectiveness of interaction with an anthropomorphic robot is debatable and depends on multiple factors [25]. We believe that one of the most natural ways to study the effectiveness of robotic assistants is to create games where the outcome is defined by a set of rules. Games allow us to study the cooperative performance of co-agents under controlled conditions, which at the same time are a natural part of the activity, rather than imposed constraints.

In the experiment described below, we sought to quantify human joint activity with an anthropomorphic F-2 robot (fig. 1) during a cooperative game. The robot was contrasted with an equally proficient *program* that was represented more as a “software game tool” rather than an “assisting companion”. We evaluated the effectiveness of human-with-robot and human-with-program performance during cooperative play and hypothesized that it would be higher when playing with the robot. We also tested the social Simon effect and assumed that it would emerge during cooperation with the F-2. In addition, we examined the difference between participants’ experiences in these conditions using Likert scales and surveys. According to our hypothesis, subjects were expected to rate the interaction with the robot as more comfortable, believing the robot to be a better assistant than the program.

Figure 1: the F-2 robot

2. Methods

2.1 Participants

In total, 36 naïve healthy volunteers (18 males and 18 females, aged 25.03 ± 4.59 years, M ± SD) participated in this study. Of these, 34 stated that they were right-handed and 2 claimed to be left-handed. All participants gave informed consent prior to their involvement in the experiment. The experimental procedures were approved by the local ethics committee and were in agreement with the institutional and national guidelines for experiments with human subjects, as well as with the Declaration of Helsinki. The minimum sample size of 36 participants was determined by using

G*Power 3.1 [26]: we calculated it for one group ANOVA with 4 repeated measures, with the effect size f=0.25, error probability α=0.05 and power (1-β)=0.95.

2.2 Experimental design and procedure

In the experiment, a participant was seated in front of a monitor and was playing the novel game that we called “CandyHunter”. During the course of the game, candies appeared in random cells on a 5x8 playfield (Fig. 2). The participant (from now on, *the player*) had to “snatch” them as quickly as possible by pressing a key, corresponding to the candy color (6 colors total): this correspondence had been explained to the player prior to the game and remained at the bottom of the screen during the whole game. A candy of each color could randomly appear in any cell on the game field. Three types of candies could be “snatched” by the keys for the left hand (“q”, “w”, “e”), and three candies – by the keys for the right hand (“7”, “8”, “9” on the Numpad). In single player mode, all six of the keys were used. This design served as a modification of the Simon ask, arranged in the form of a game. The 5x8 design of the grid in contrast to the standard left/right distinction was adopted to present the stimuli in context of something that resembled a mobile game, and not in an experimental task. This way we wanted to make the experiment more engaging for the participants without substantially changing the procedure of the Simon task: the distinction between the left and right halves of the screen was maintained.

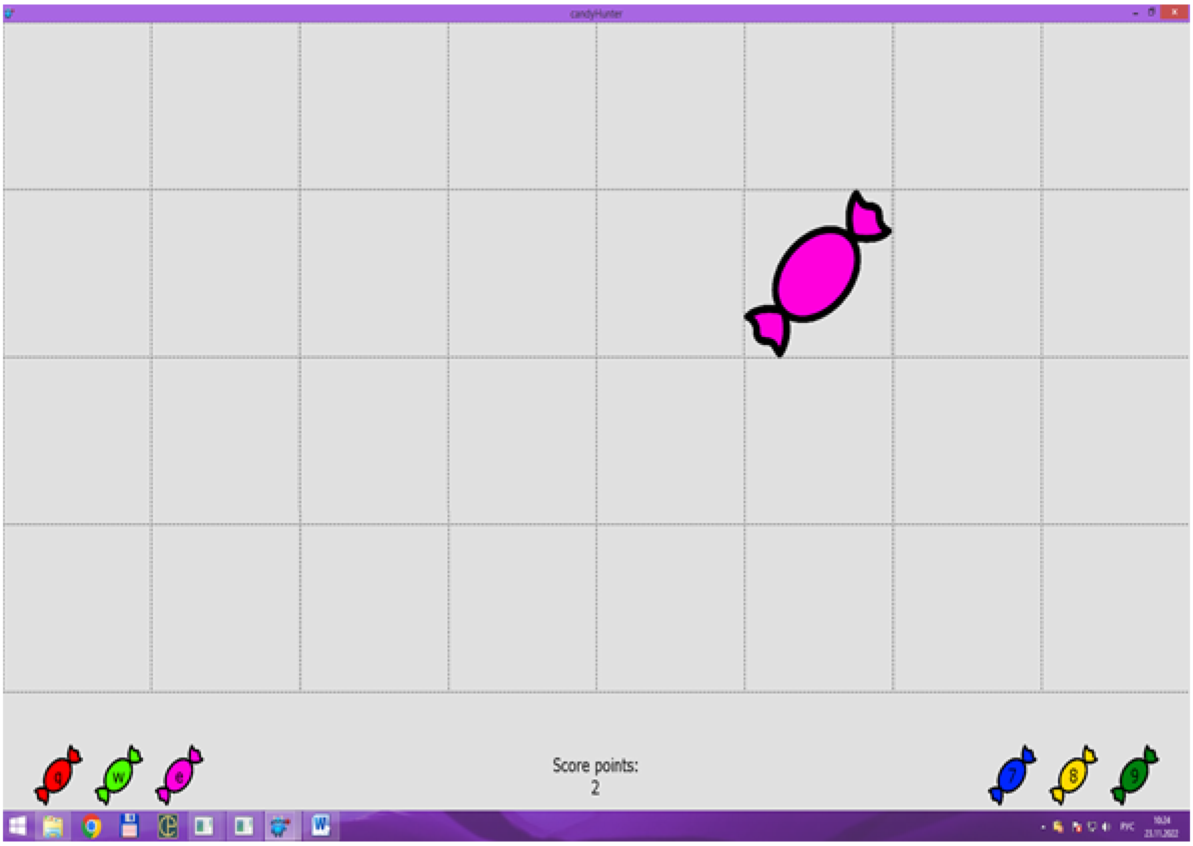

Figure 2: CandyHunter interface: the player has to press "e" button to snatch the purple candy

When the player pressed the correct key, the candy would disappear, accompanied by a popping sound, and the player would get points. The number of points depended on the player's reaction time and dropped as a negative exponential function. Pressing the wrong key would trigger an error sound, and result in significant penalty points. Consequently, it was more profitable for the player to look for the right key rather than to react immediately with a random press.

In the cooperative mode, the assistant took control over three types of candies ("7", "8", and "9"), freeing up the player's right hand. While the player used all of the six keys in the single games, they would only use the left three keys in the cooperative games. The mechanics of the game remained the same in the cooperative mode: the candy appeared on the screen one at a time. The player or the assistant "snatched" candy in turns, but they could get several candies consequently, as the type of candy was random. The points earned by the assistant were assigned to the player. The assistant made no mistakes, but the speed (and, thus, quality) of his help could be either high or low in different modes. In "slow" mode, the assistant took longer to respond to the candy than in "fast" mode, which resulted in less points. Reaction times in slow mode randomly ranged from 1000 to 1300 ms, while in fast mode – randomly ranged between 500 and 800 ms. Fast and slow modes alternated in different sessions of the experiment.

When a participant played together with the robot, the robot had been raising its arm to manifest snatching a corresponding candy (candy of a color, delegated to the responsibility of the robot). If the candy appeared on the left side of the screen, the robot would slightly turn its head to the left and raise its left hand, and if it appeared on the right side, it would turn its head to the right and raise its right hand. The robot was in the player's field of view, standing on the table to the side of the keyboard (Fig. 3). Before the experiment, the robot greeted the player to gain more sympathy. In turn, the P-1 program was not visually or audibly represented: the candies delegated to it would just disappear after the delay. When the robot was not supposed to assist in the game, it was idle. During the experiment, the robot stayed in the same place on the table. If the disposition of the robot somehow influences the behavior of the participant and creates the effect of social presence, this effect should be similar for all the experimental conditions.

Figure 3: A participant playing CandyHunter game together with the F-2 robot

In total, the experiment included five types of conditions:

- Game in single-player mode.
- Cooperative game with the program: half of the candy types are delegated to the program. The program responded faster in one mode (FProg), and slower in another (SProg).
- Cooperative game with the anthropomorphic robot F-2: half of the candy types are delegated to the robot. Robot's performance could also be either fast (FRobot) or slow (SRobot). The two latter modes were similar in all the details, except for the robot moving at the side of the player.

Altogether during the experiment, the player went through seven game sessions of five minutes each. In the first, fourth, and seventh sessions they played alone. In between these sessions, they played with the assistants, so that consecutive sessions were played with different assistants, one of them in "slow" mode, and the other in "fast" mode, giving 4 combinations of sessions. A particular combination of modes was selected randomly for each participant. A flowchart with possible orders of sessions is shown in Figure 4.

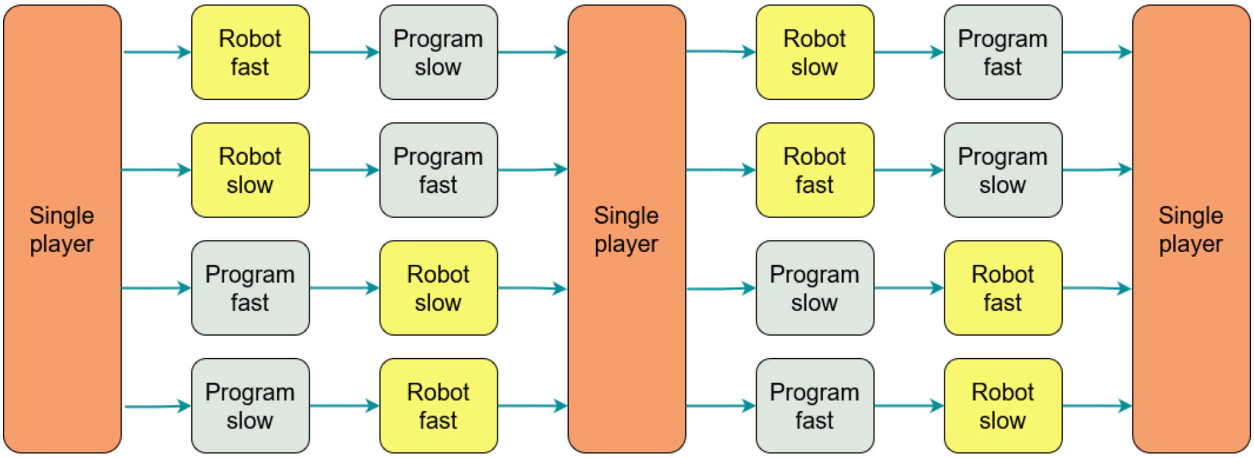

Figure 4: Design of the experiment. Branches denote different variants of session order. The boxes denote game sessions

After completing all the sessions, the participant filled out the questionnaire. The following questions had to be scaled from 1 to 10 (the questions were duplicated for the robot and the program): *Did you enjoy playing together with the F-2 robot/P-1 program?*, *How much help did the F-2 robot/P-1 program provide in the game?*, *To what extent did the effectiveness of cooperative play depend on the F-2 robot/P-1 program?*, *How often do you think you made mistakes when playing together with the F-2 robot/P-1 program?*, *How often do you think the F-2 robot/P-1 program made mistakes?* In addition, there was a separate question about the robot: *Did you pay attention to the actions of the F-2 robot during cooperative play?* Finally, participants had to write a report about the subjective difference between the gameplay with the robot and the program.

We designed this questionnaire having in mind the specific features of the experimental procedure, i.e. the game. The existing questionnaires on the perceived effectiveness of a robot (e.g. [27]) and the enjoyability of human-robot interaction (e.g. [28]) are tailored for certain categories of situations, be it communication with a robot or tasks that imply different modes of robot control. The survey served a secondary role in our study: we intended to use it to further validate other results and also get feedback on the F-2 robot.

We decided not to include questions on perceived agency of the robot, since we did not expect the participants to verbally attribute agency to the robot when asked. The embodied agency and anthropomorphism were its design features. We expected to validate these features by exploring the social Simon effect, that is based on the low-level phenomena associated with third-person perception of agency, and not with explicit judgments. In this regard, we stand with the authors who propose a distinction between low-level and high-level sense of agency [29–31].

2.3 Statistical analysis

In our study, we analyzed the number of game points scored by the players, the reaction times of the participants, the number of errors made during the game, and the subjective scores given on a 10-point scale. We used the repeated measures ANOVA to analyze the scores and reaction times. The Friedman test, a non-parametric counterpart of the repeated measures ANOVA, was used to compare the number of errors. Pairwise subjective scores were compared using the signed-rank Wilcoxon test. We counteracted the multiple comparisons problem by running the Benjamini-Hochberg [32] procedure (FDR) with a false discovery rate Q=0.05. Statistical analysis was performed using Statistica software (Statsoft, USA).

3. Results

3.1 Effectiveness of interaction

To compare the effectiveness of human interaction with the two assistants, we analyzed total scores in the cooperative sessions. Single-player sessions were not included in this analysis, because in this mode participants did not share stimuli with the assistants. In our experimental design, we did not distinguish points scored by the player or the assistant. Given that the length of each session was determined by the 5-minute limit, the number of points scored by the assistant in each session depended on the player's performance: the faster the human played, the more candies the assistant was able to snatch. The two assistants – robot or program – were playing uniformly in the fast and slow modes. So in cooperative sessions we considered the points earned by the participants alone. This left us with a 2x2 design. Two-way repeated measures ANOVA showed significance of the assistant factor (F(1, 35)=16.383, p=.00027) but not of speed factor (F(1, 35)=.799, p=.377). Factor interaction was significant (F(1, 35)=28.436, p=0.00001)) (see Fig. 5). Fisher's LSD post hoc test showed a significant difference between the FRobot and the SRobot sessions (p=.005), the FProg and the SProg sessions (p=.00006), and the FRobot session and the FProg session (p<.00001). The difference between SRobot and SProg conditions was not significant (p=.723). We did not conduct other post-hoc tests, as they were not of interest to us. The participants scored more points with the fast robot, than with the slow one, but the difference was reverse in the case of the FProg and SProg conditions: the participants played better with a slow program, than with the fast one. Consequently, the participants scored more points with a fast robot than with a fast program.

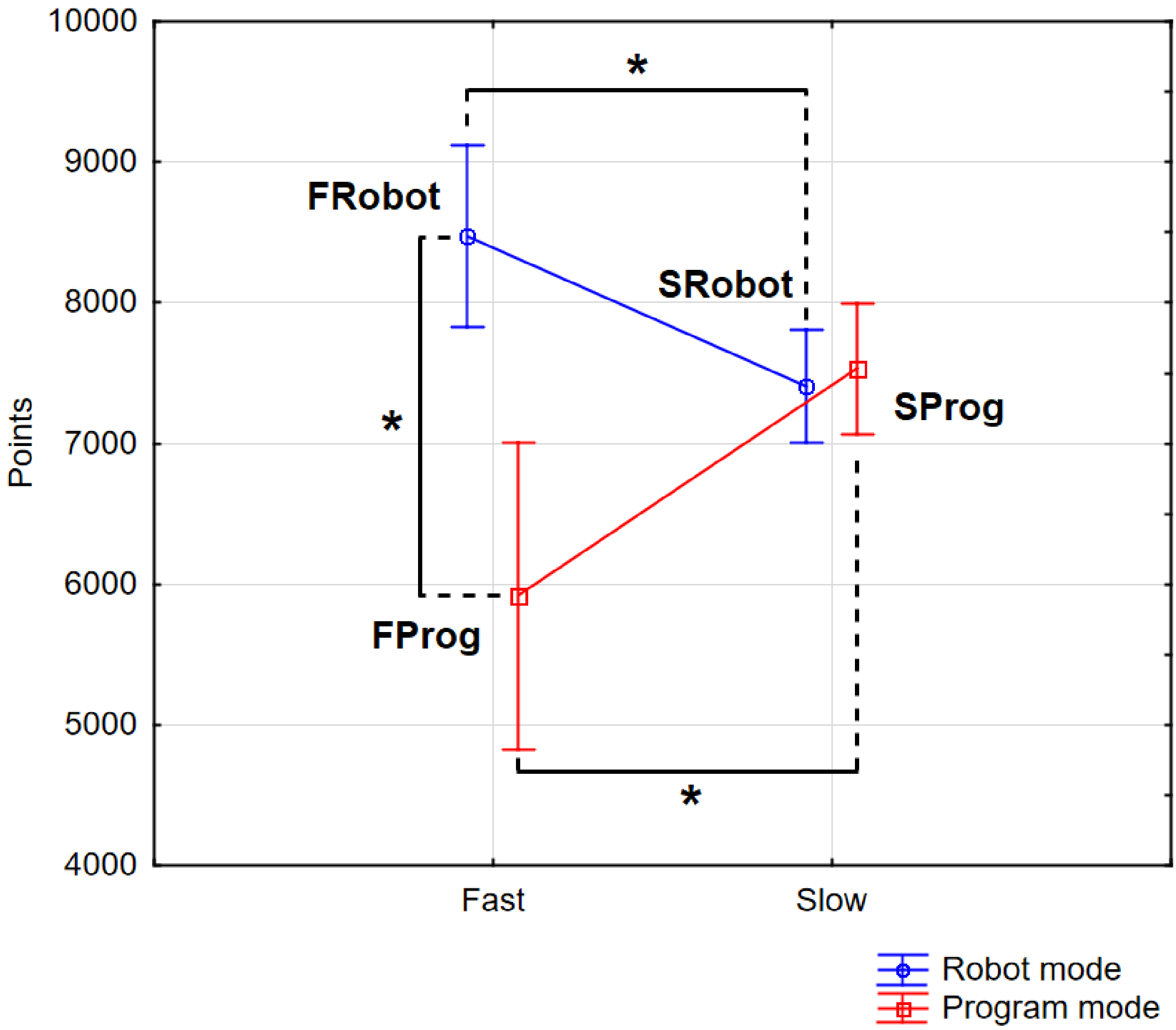

Figure 5: Median scores in assistant sessions. Vertical lines indicate 95% confidence intervals. The asterisks highlight the significant differences

3.2 Reaction times and errors

We also examined the median reaction times of the players. We included all the seven sessions in this analysis to see how the assistants affected participants' reaction times. One-way repeated measures ANOVA showed significance of the effect (F(6, 210)=78.183, p<0.0001) (see Fig. 6). Fisher's LSD post-hoc test showed a difference between all single-player sessions and assistant sessions (p<0.0001). There were differences between reaction times in the three single-player sessions: between the first and the second sessions (p<0.0001), and between the second and the third sessions (p=0.088), indicating that the participants gradually improved their skills. Post hoc tests also showed a difference between the FRobot and SRobot sessions (p=0.0156), but not between the FProg and SProg sessions (p=0.457). There were no differences between the FRobot and FProg sessions (p=0.339), as well as between SRobot and SProg sessions (p=0.465). After running the Benjamini-Hochberg procedure, all the discoveries remained significant. The major result from this analysis was that the speed of the robot influenced the speed of the player, which could not be said for the speed of the program.

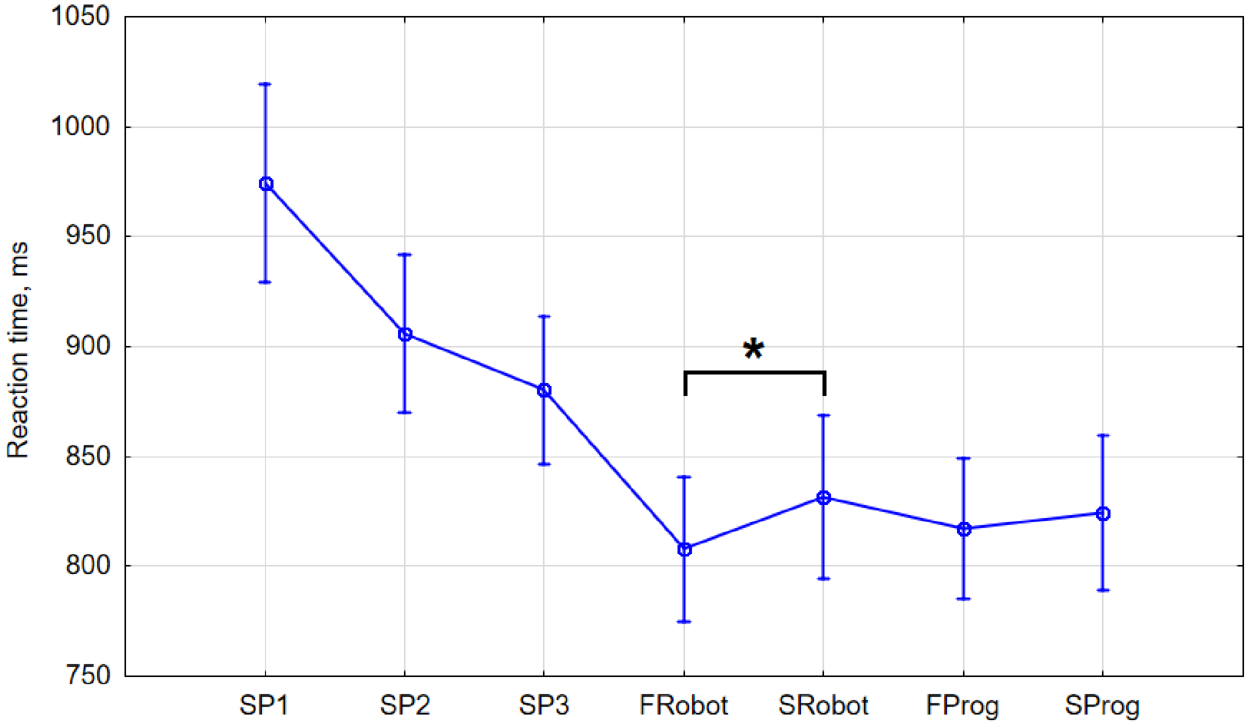

Figure 6: Median reaction times in all sessions (sessions are ordered by type). Vertical lines indicate 95% confidence intervals. SP denotes single-player game, the asterisk highlights the significant difference between the FRobot and the SRobot sessions

To test the social Simon effect during the joint agency with the robot, we once again considered the 4 assistant sessions. Recall that in these conditions, the participant only pressed keys with their left hand. In the 4 conditions we subtracted the median reaction times for stimuli appearing on the right side from those appearing on the left. Two-way repeated measures ANOVA showed no significant effect for both the assistant factor (F(1, 35)=0.56, p=0.459) and speed factor (F(1, 35)=0.1, p=0. 753). Thus, the social Simon effect has not been replicated for cooperative play with the F-2 robot.

We also considered numbers of errors made by the participants in sessions with the assistants. We did not consider the single player sessions, as the participants had more opportunity for errors in these sessions. For the number of errors in the assistant sessions (which did not exceed 20) the Friedman test found a significant effect: $\chi^2 = 32.98$, p<0.00001 (Fig. 7). Post-hoc analysis using pairwise Wilcoxon tests showed significant differences between the FRobot and SRobot sessions (p=0.0001) and FProg and SProg sessions (p=0.0004). Participants more frequently made errors with “fast" assistants than with “slow” assistants. The Benjamini-Hochberg procedure confirmed the significance of results.

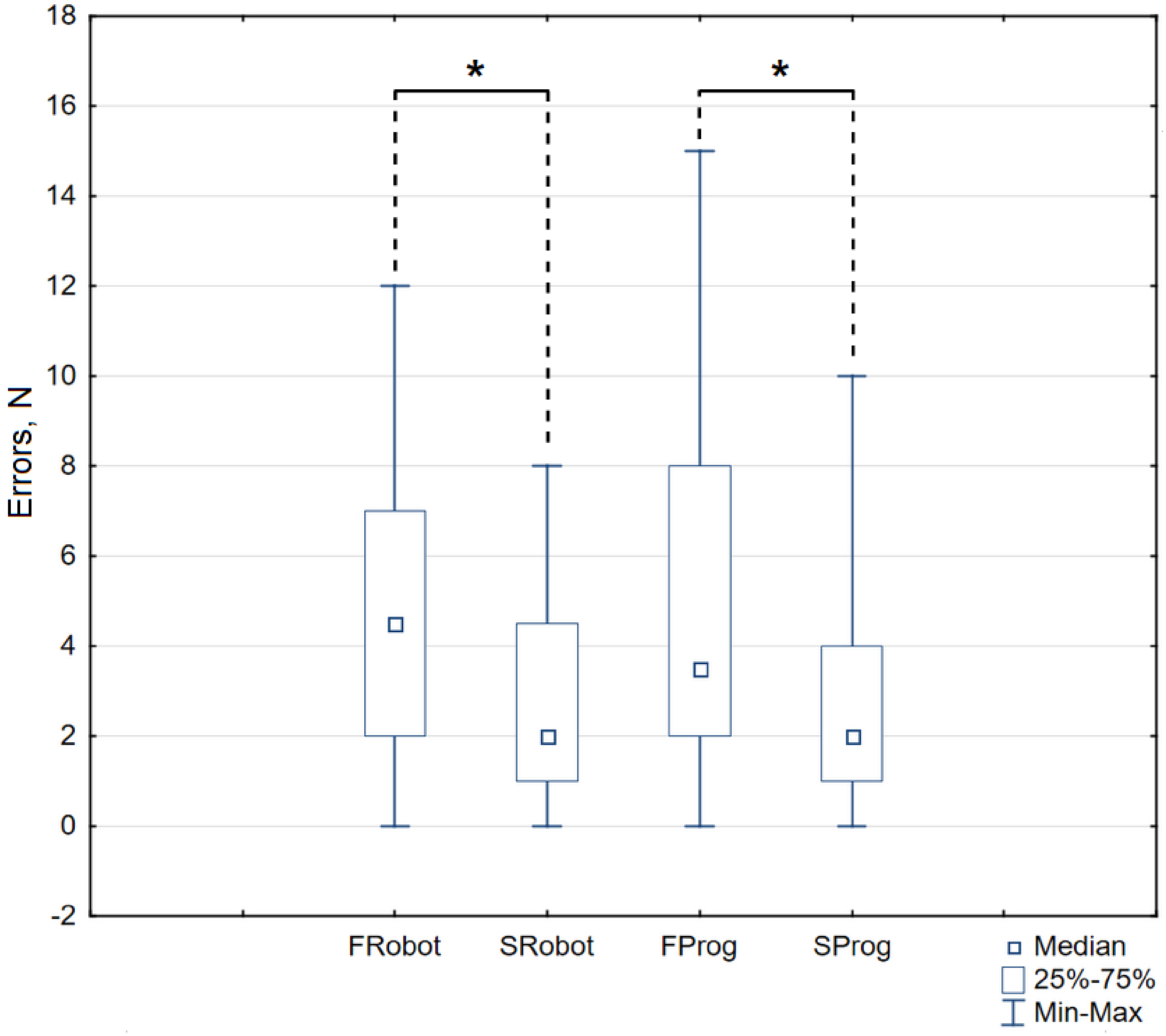

Figure 7: Numbers of errors in experimental sessions. The asterisks highlight significant differences between "fast" and "slow" assistant sessions

3.3 Survey

We also analyzed the answers to the questions on 10-point scales. For the answers to the question *Did you enjoy playing together with …?* the Wilcoxon test showed a significant difference between the scores for F-2 and the program (Z=3.5, p=0.0004): participants were more comfortable, while playing with F-2. Comparisons of other scores showed no significant results. A total of 6 pairwise comparisons of robot and program surveys were conducted, and the significant result was confirmed when accounting multiple comparisons by the Benjamini-Hochberg procedure. In addition to the scales, we processed the subjective reports of the participants. There was a recurring element in the reports about the difference between the two assistants: six participants stated that the sounds of the robot helped them play, while another six said that the robot distracted them during the game. For convenience, we will refer to these two sets of participants as subgroups, while keeping in mind that their emergence was not entailed by our experimental design.

We compared the score of participants from one subgroup with the score of participants from another subgroup via Student’s t-test and found a significant difference between the first single-player sessions (t=2.88; p=.016), the sessions with the fast robot (t=3.16; p=0.01) and the fast program (t=2.45; p=.034). According to these tests, participants who were irritated by the sound generated by the robot overall gained less points in respective conditions. However, these results were not significant when corrected for multiple comparisons using the Benjamini-Hochberg procedure.

4. Discussion

Our study focused on comparing the user’s experience during a cooperative game with an anthropomorphic robot or an assistant program. We were interested in both quantitative properties of the game and participants’ opinions about working with the robot. We found a difference in the efficiency of the user's interaction with the robot and the program. In the cooperative game mode with the “fast” F-2 robot, participants scored significantly more points than in other game modes. Meanwhile, when playing with the “fast” program, they scored significantly less points, than in condition with the “slow” program. Note that the only difference between the mode with the “fast”/“slow” robot and the mode with the “fast”/“slow” program was only in F-2’s movements, as the assistants reacted to the candy equally fast and made no errors. Interestingly, the difference between the fast robot and the fast program in scores does not reproduce separately for reaction time and number of errors – it was the integral characteristic of the game that differed. Also, the analysis showed that differences in numbers of errors were not always accompanied by significant differences in reaction times: the players made more errors in the condition with the fast program, than with the slow program, but the same difference did not obtain for the reaction times in these conditions. Besides from efficiency, F-2 *imposed* its pace on the players, as opposed to the program. If the robot responded quicker, so did the player. In addition, according to the survey results, the participants found playing with F-2 more comfortable than playing with the program.

The difference between the two assistants amounted to features in two sensory modalities. F-2 was designed to appear as an embodied agent: it had a physical manifestation that the P-1 program lacked. When acting as an assistant, F-2 performed simple movements. In addition to a visual difference between the assistants there an audible one: movements of F-2 were accompanied by sounds of servo drives. These two features promote two possible explanations of our results. According to one of them, differences in efficiency were due to the fact that the participants visually perceived F-2 as a co-agent, and this perception of agency improved their performance in the game, as joint agency between the player and the robot emerged.

The alternative explanation of efficiency increase has to do with the sounds produced by the robot. It is possible that the robot acted as a metronome, and set a higher pace for the participants. However, as the type of appearing candy was random, the robot did not move periodically: the interval between the robot's turns varied. Candies delegated to the player or the robot could appear consequently. In a free-form survey, fourteen subjects mentioned that they had paid attention to the sounds. It is worth noting that six of them had thought that sounds of the robot helped them to play, another six indicated that the sounds had distracted them, and two did not comment whether the sounds were useful. Also note that the benefit indicated in the surveys from sound assistance was not apparent statistically when the scores were assessed. However, this statistical test involved a small number of participants.

Given our experiment design and results, the explanation based around the sounds produced by the robot cannot be completely ruled out. In order to test it, the experiment has to be replicated with presentation of sounds in conditions where participants play together with a program, or with exclusion of all sounds by utilizing earmuffs. Based on a lack of concordance between participant scores and positive or negative references to sounds in a survey, and also on the aperiodicity of robot movements, we consider the explanation based on joint agency when playing with F-2 to be more favorable, although more research is needed to further support this conclusion. The inability to account for the impact of noises generated by the robot is one of the main limitations of our study.

In this study, we also expected to reproduce the social Simon effect in cooperative sessions with the robot. We assumed that this effect would emerge when playing with the robot, but not with the program. However, the effect did not obtain, and it could happen due to different reasons. The robot waved its arms in response to the candy, while the participant pressed the keys – so the co-representation of the action might not have arisen when the movements were different. The social Simon effect depends not only on perceived likeness of another agent, but on the similarity of their movements [33]. Also, the shape of the robot arm was not humanoid: it resembled a fish fin and lacked digits. Since even human-like robotic hands are not always sufficient to bias attention [34], the arms of F-2 could not have triggered perceptual mechanisms which normally shift attention to the partner's hand during a joint task. To our knowledge, in all studies of social Simon task involving robots, only robots with humanoid hands were used.

Nevertheless, it is possible that the F-2 was not perceived as a co-agent by the participants. It should be noted, that in one of the experiments where the social Simon effect was reproduced using an anthropomorphic robot [18], the presence of the effect depended on the participants' preconditioning, not the type of robot. This effect was not reproduced in a more recent study [20], where the effect emerged irrespective of preconditioning. It could be due to differences in robot design. In our experiment, a semblance of preconditioning was created by the greeting gesture of the F-2 before the experiment, but we did not inform the participants about the cognitive abilities of the robot. Overall, we cannot draw strong conclusions from these results, as there are several possibilities.

Our findings indicate that the interaction with the F-2 robot was more effective. In the game, the responsibilities between the human and the robot were equally divided, with the assistant acting as an equal partner. Probably, it is under such conditions that the emergence of joint agency happens. Given our results, we believe that the development of human-machine interaction in the form of joint agency is a promising endeavor, and can significantly improve human-robot joint activity. In order to prove this thesis in a general way, the results we obtained in the case of a reaction game should be replicated in other joint tasks. The impossibility of replication is one of the main challenges in studies of human-robot interaction [35], and attempting it is crucial. In a world where machines become more and more intelligent, interaction with robotic systems could be more productive if presented as cooperation, and not simply tool use. Besides from efficiency, survey results from our study indicate that playing with the robot was more enjoyable. Adopting intentional stance [36] toward robots, that is conceiving them as agents, is potentially beneficial for human coexistence with them [37]. By comparing human interaction with an embodied robot and a software tool, we have taken a step towards testing this assumption in terms of effectiveness.

If our results were replicated in different settings, it would imply that the design of electronic assistants should be more anthropomorphic. The optimal degree of anthropomorphism in these scenarios has to be studied empirically, as with increasing anthropomorphism there is a probability of the manifestation of the uncanny valley effect [38]. However, note that the effect might not be significant for the perception of robotic agency, while being prominent for the ascription of experience to robots [39]. The F-2 robot that we used in this study was designed with an intention to avoid the uncanny valley effect. Further experimentation should also show whether embodiment of a robot is significant: in our design, the program did not have a visual representation. It would be fruitful to compare an embodied robot with a software assistant that has an icon with a face on the computer screen.

5. Conclusion

In our study of human-machine interaction, participants played a game that required reacting to visual stimuli. We contrasted cooperative game modes with two different assistants – an anthropomorphic robot and a program. The modes differed only in the design of the assistant: they were equal in terms of efficiency. Also, these assistants had high or low reaction times depending on the condition. In games with slow assistants, participant’s scores did not differ significantly. However, participants earned more points when the speed of the robot was high, and earned less points when playing with the “fast” program. According to the survey, participants preferred playing with the robot. Meanwhile, we could not reproduce the social Simon effect for the joint task with the robot, as the movements of participants and the robot were different. We believe our findings suggest that engagement of anthropomorphic robots in collaborative activities with humans could lead to an increase in human performance and satisfaction.

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