COVR Award Agreement: AA9342566381

Collaborative Robots' Perceived Safety
CROPS

Deliverable 2.4: Experimental validation – collaboration with the robot

Date: 30. 6. 2021

Authors: *Luka Komidar, Kristina Rakinić, Gaja Zager Kocjan, Kristina Nikolovska, Anja Podlesek, Matjaž Mihelj, Sebastjan Šlajpah*

University of Ljubljana Faculty of Electrical Engineering

Univerza v Ljubljani Filozofska fakulteta Oddelek za psihologijo

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 779966.

Contents

1 Introduction

In this document, the results of Experiment 2 (collaboration with the robot) are presented. The following chapters cover the procedure of the experiment, the experimental design (independent and dependent variables), and the results of the experiment. More detailed descriptions of the experimental setup and procedure are presented in Deliverable 2.2 and Deliverable 2.3.

2 Method

2.1 Sample

There were 33 participants in total, 12 of whom were men. The mean age of the participants was 26.8 years (min = 19; max = 39; SD = 5.7). Most participants (n = 14) had a bachelor degree, followed by participants with a master's degree (n = 8), and those with finished high school (n = 8). Two participants had a PhD and one completed a vocational high school. The sample included 23 students and 10 employed participants. More than half of the participants (n = 20) worked or were studying for a profession in the field of social sciences and humanities. None of the participants had previously worked or had other important experience (e.g., managing, cooperation) with such robotic arms. Ten participants had some superficial experience with other robots, especially with iRobot Roomba.

2.2 Independent variables – robots' parameters

We examined the influence of three independent variables on the selected self-reported measures.

Scenario:

- industrial (assembling of a small electronic device) and
- laboratory (simulation of Kirby Bauer method for testing efficacy of antibiotics on bacteria).

Type of tool (Figure 1)**:**

- safe (industrial: a box enclosure, laboratory: a petri dish),
- dangerous (industrial: testing leads, laboratory: a pipette;) and
- a combination of both.

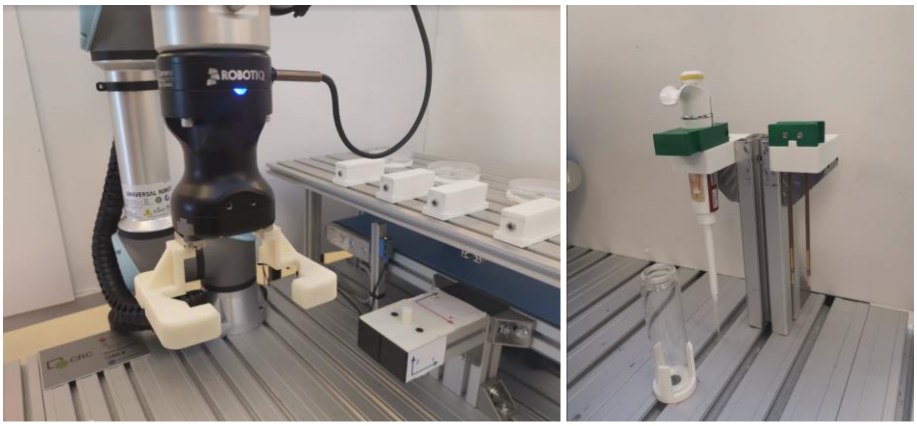

Figure 1: Robot's gripper with 3D printed fingers for gripping box enclosure/petri dish - safe tool (left), and testing leads and pippete - dangerous tool (right)

Robot's TCP velocity:

- slow (0.3 m/s) and
- fast (0.75 m/s).

With such a research plan, we obtained 12 (2 x 3 x 2) experimental conditions. Every participant was exposed to each of the conditions only once, and the order of the conditions (defined by scenario, velocity and tool type) within each participant was randomized.

2.3 Dependent variables

Variables measured in the Experiment 2 are listed below in the order as they were measured during the experiment.

Demographic variables

Participants reported their gender, age, education level, and employment status.

The main research questions (RQ)

a) Perceived level of pleasure and arousal

Participants had to select the manikin (Figure 2 for pleasure and Figure 3 for arousal) that best represented how they felt when collaborating with the robot. For each condition, they gave one response about their level of pleasure and one about their level of arousal.

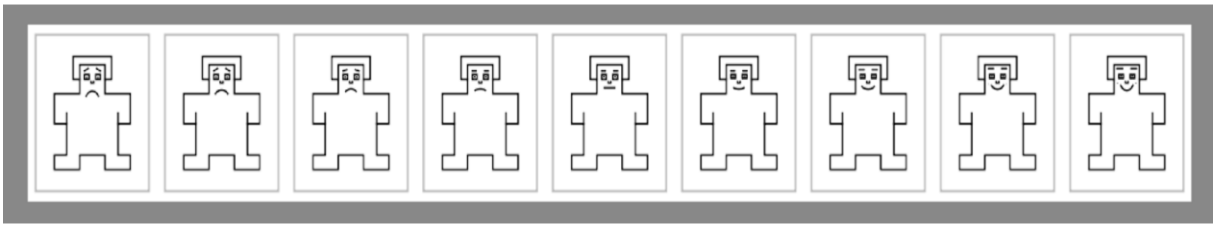

Figure 2: The 9-point Self-Assessment Manikins for measuring pleasure.

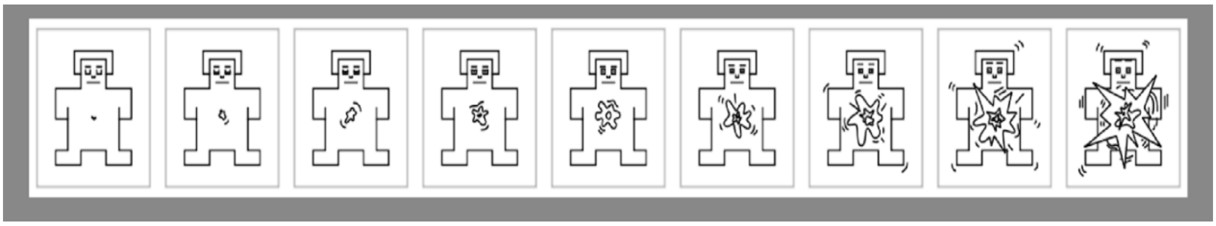

Figure 3: The 9-point Self-Assessment Manikins for measuring arousal.

b) Perceived safety and intention to collaborate with this robotic arm

For each of the conditions the participants responded to the question »How safe did you find the robot's movement?« on a 9-point scale (1 – totally unsafe, 9 – totally safe). They also responded to the question »To what extent would you collaborate in the future with a robot?« on a 9-point scale (1 – not at all, 9 – most certainly).

2.4 Procedure of Experiment 2

All measurements took place at the Faculty of Electrical Engineering, University of Ljubljana, in the Laboratory of Robotics. Participants were asked to come to the faculty where they were accepted by the executive researcher from the Departments of Psychology and Robotics. First, the researcher from the Department of Psychology explained the purpose of the study and its framework. Before starting, the participants read and signed the informed consent that was necessary for participation in the study. The participants then filled in demographic questions. This part of the procedure took approximately 10 minutes.

Participants were asked to sit down at a table, which was their working space. There was also a robot on the table and all the peripherals (Figure 4 and Figure 5). On the left side of the working area sat a researcher who operated the robot, and on the right a researcher from the Department of Psychology, who was writing down the participants' answers about their feelings (Figure 6). An electrical engineering student also participated in the experiment, who helped with preparing the work tools. Participants were first briefly introduced to the course of the experiment. They were told that they will participate in two work scenarios, one imitating the industrial environment and the other the laboratory environment. Within these scenarios, they will perform different steps of the task, and after each trial, they will report about their level of pleasure and arousal, how safe they found the robot's movement, and to what extent they would be willing to work with the robot in the future. Participants then began the experiment with the industrial or laboratory scenario. The researcher first introduced them to all five steps of each situation. All the steps of both scenarios are presented in detail in Deliverable 2.2. Participants had a trial practice before each of the scenarios to familiarize themselves with the workflow. Before each trial, the researcher once again explained to the participants the course of the task so that the participants knew what the robot would do and what their task was. This part of the experiment took half an hour on average.

After the experiment, participants were asked to share observations, feelings and experiences they had during the experiment. The executive researcher from the Department of Psychology wrote down their observations (Figure 6). The executive researchers thanked the participants for their time and cooperation and accompanied them from the faculty.

Figure 4: Shared working area of the participant and the robot.

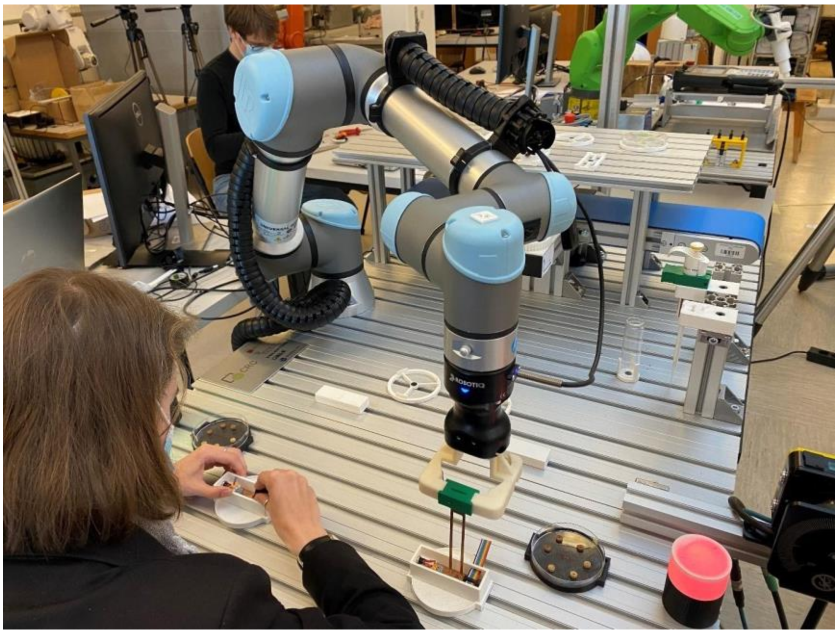

Figure 5: A participant and the robot working simultaneously on their working tasks.

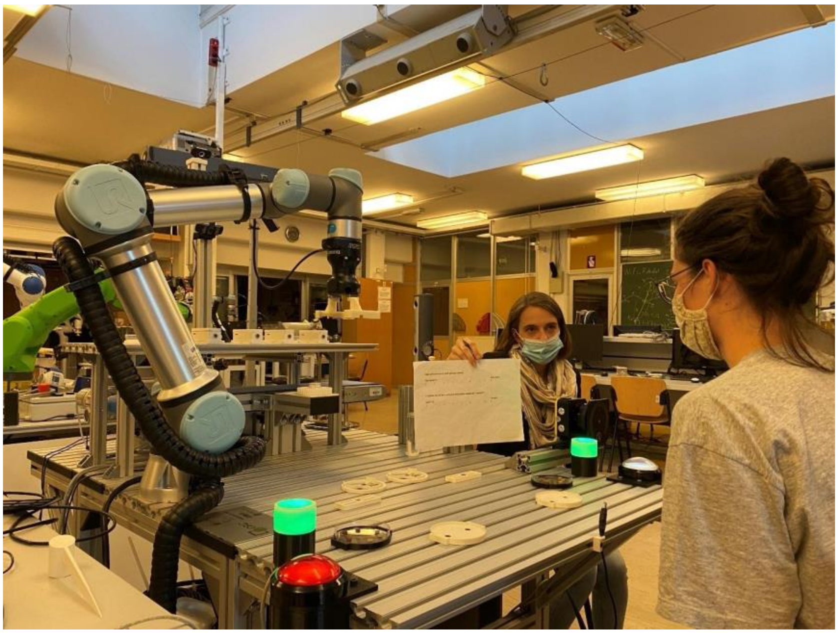

Figure 6: A participant is reporting to the researcher about her feelings after one of the experimental conditions.

3 Results of Experiment 2

The main goal of Experiment 2 was to examine the effects of scenario (industrial vs. laboratory), velocity of the robot's movement (slow [0.3 m/s] vs. fast [0.75 m/s]), and tool type (safe, dangerous, and both) on four self-report experiential measures, i.e., perceived pleasure, arousal, safety, and intention to collaborate with the robot. Each of the following four chapters contains the results of a three-way repeated measures ANOVA for studying the effects of the three independent variables on one of the four outcome variables.

3.1 Pleasure

Overall, the average pleasure ratings were very high across all experimental conditions ($M_{tot} = 8.1$, $SD_{tot} = 1.2$). The main effects of velocity and tool type were statistically significant, but rather small (Table 1). The participants reported higher levels of pleasure when the robot was moving slowly ($M = 8.3$, $SD = 0.7$) compared to when it was moving fast ($M = 7.9$, $SD = 1.0$). Concerning tool type (Figure 7), the participants felt less pleasure when the robot was using only the dangerous tool than when it was using either the safe or both tools. We also found an almost negligible, but statistically significant two-way interaction between velocity and tool type (Figure 8); the decrease in pleasure levels from slow to fast robot movement conditions was larger in the dangerous tool condition.

Table 1: Summary of a 3-way repeated measures ANOVA for the effects of scenario, velocity, and tool type on pleasure.

Source of variation	SS	df	MS	F	p	η_g^2
Scenario	1.010	1	1.010	0.937	.340	.002
Residuals	34.490	32	1.078			
Velocity	16.980	1	16.980	16.708	< .001	.033
Residuals	32.520	32	1.016			
Tool	13.096	2	6.548	6.627	.002	.026
Residuals	63.237	64	0.988			
Scenario x Velocity	0.495	1	0.495	1.439	.239	< .001
Residuals	11.005	32	0.344			
Scenario x Tool	3.035	2	1.518	2.371	.102	.006
Residuals	40.965	64	0.640			
Velocity x Tool	4.096	2	2.048	3.369	.041	.008
Residuals	38.904	64	0.608			
Scenario x Velocity x Tool	0.520	2	0.260	0.401	.671	.001
Residuals	41.480	64	0.648			

η_g^2 – generalized eta squared

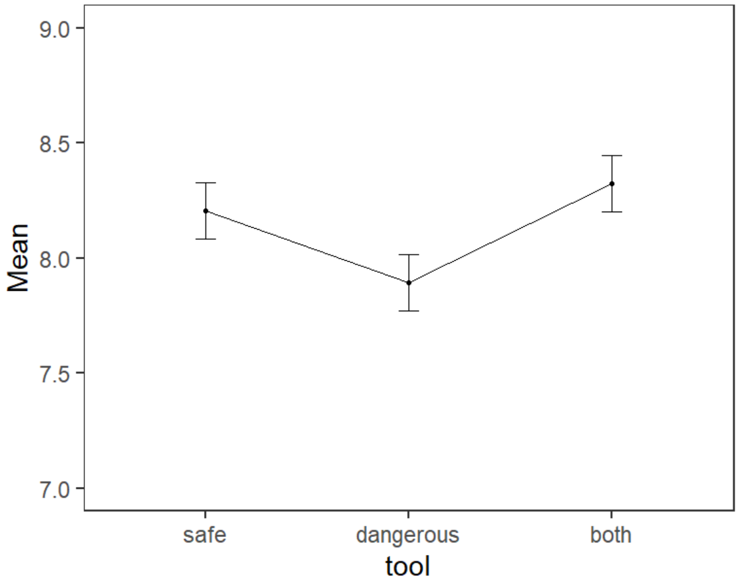

Figure 7: The main effect of tool type on pleasure (the bars represent Fisher's least significant differences)

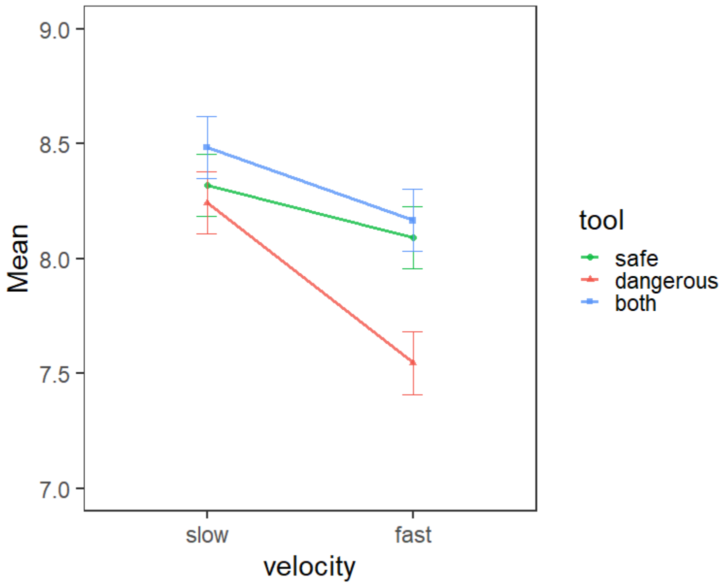

Figure 8: The two-way interaction between velocity and tool type on pleasure (the bars represent Fisher's least significant differences).

3.2 Arousal

The participants' arousal levels were low across all conditions ($M_{tot} = 1.7$, $SD_{tot} = 1.1$). As was the case with pleasure, velocity of the robot's movement and tool type used had significant but small main effects on arousal levels (Table 2). The participants' average arousal was lower when the robot was moving slowly ($M = 1.5$, $SD = 0.5$) than when it was moving fast ($M = 2.0$, $SD = 1.0$). The effect of tool type showed that the participants' arousal was highest when the robot was using the dangerous tools (testing leads or a pipette; Figure 9).

The ANOVA also revealed a small interaction effect between scenario and tool type (Figure 10). The scenario affected the participants' arousal only when the robot was using the safe tool – the participants were slightly more aroused when they were collaborating with the robot in the industrial scenario.

Table 2: Summary of a 3-way repeated measures ANOVA for the effects of scenario, velocity, and tool type on arousal.

Source of variation	SS	df	MS	F	p	η_g^2
Scenario	1.980	1	1.980	1.473	.234	.005
Residuals	43.020	32	1.344			
Velocity	17.818	1	17.818	15.065	< .001	.043
Residuals	37.848	32	1.183			
Tool	12.015	2	6.008	10.785	< .001	.029
Residuals	35.652	64	0.557			
Scenario x Velocity	0.091	1	0.091	0.294	.592	< .001
Residuals	9.909	32	0.310			
Scenario x Tool	3.096	2	1.548	3.550	.034	.008
Residuals	27.904	64	0.436			
Velocity x Tool	1.136	2	0.568	1.095	.341	.003
Residuals	33.197	64	0.519			
Scenario x Velocity x Tool	0.379	2	0.189	0.492	.614	< .001
Residuals	24.621	64	0.385			

η_g^2 – generalized eta squared

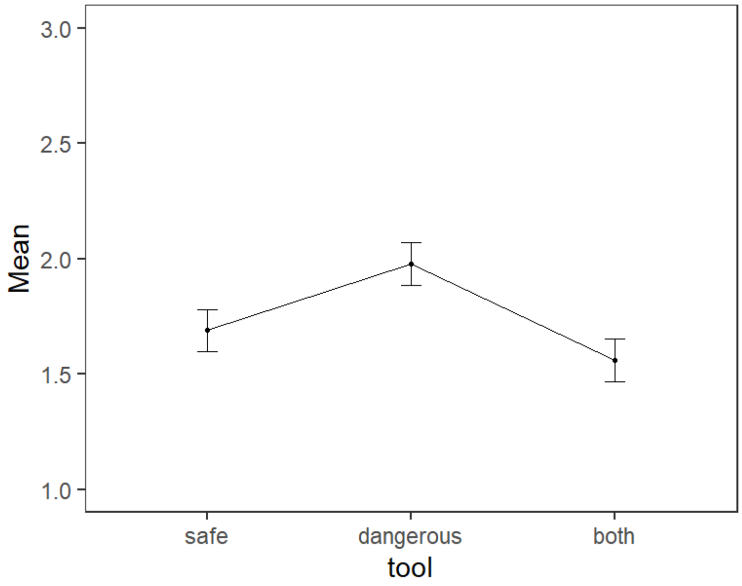

Figure 9: The main effect of tool type on arousal (the bars represent Fisher's least significant differences).

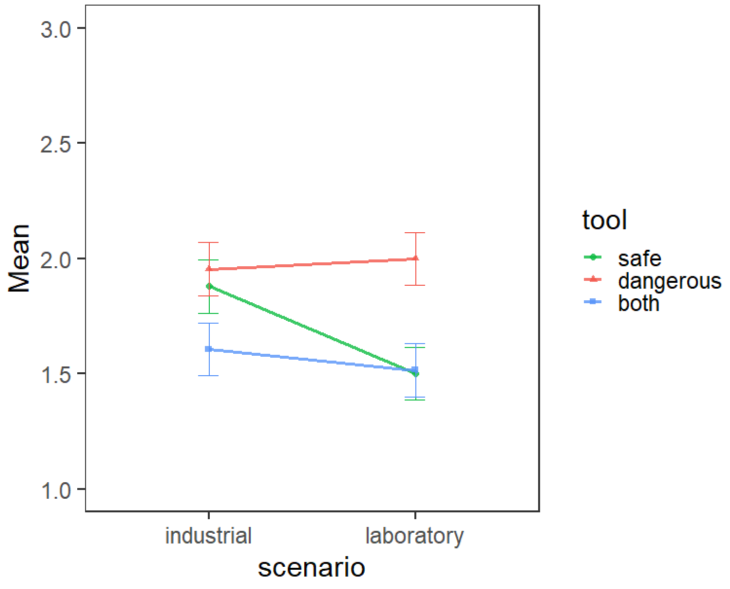

Figure 10: The two-way interaction between scenario and tool type on arousal (the bars represent Fisher's least significant differences).

3.3 Perceived safety

Average perceived safety was high in all experimental conditions ($M_{tot} = 8.5$, $SD_{tot} = 0.9$). The only statistically significant main effect was that of velocity (Table 3). The participants felt slightly more safe when the motion of the robot was slow ($M = 8.7$, $SD = 0.5$) compared to when it was fast ($M = 8.2$, $SD = 0.9$).

We also found two small but statistically significant two-way interactions, i.e., between scenario and tool (Figure 11), and between velocity and tool (Figure 12). When the robot was using only safe or both types of tool, the perceived safety was slightly higher in the laboratory scenario, while the opposite was true for the dangerous tool condition. Regarding the interaction between velocity and tool type, the effect of velocity (i.e., a decrease of perceived safety from slow to fast velocity conditions) was more pronounced when the robot was using the dangerous tools.

Table 3: Summary of a 3-way repeated measures ANOVA for the effects of scenario, velocity, and tool type on safety.

Source of variation	SS	df	MS	F	p	η_g^2
Scenario	0.730	1	0.730	1.489	.231	.002
Residuals	15.687	32	0.490			
Velocity	17.396	1	17.396	13.910	< .001	.052
Residuals	40.020	32	1.251			
Tool	3.096	2	1.548	3.011	.056	.010
Residuals	32.904	64	0.514			
Scenario x Velocity	0.730	1	0.730	3.038	.091	.002
Residuals	7.687	32	0.240			
Scenario x Tool	3.247	2	1.624	5.445	.007	.010
Residuals	19.086	64	0.298			
Velocity x Tool	2.793	2	1.396	3.797	.028	.009
Residuals	23.540	64	0.368			
Scenario x Velocity x Tool	1.308	2	0.654	2.612	.081	.004
Residuals	16.025	64	0.250			

η_g^2 – generalized eta squared

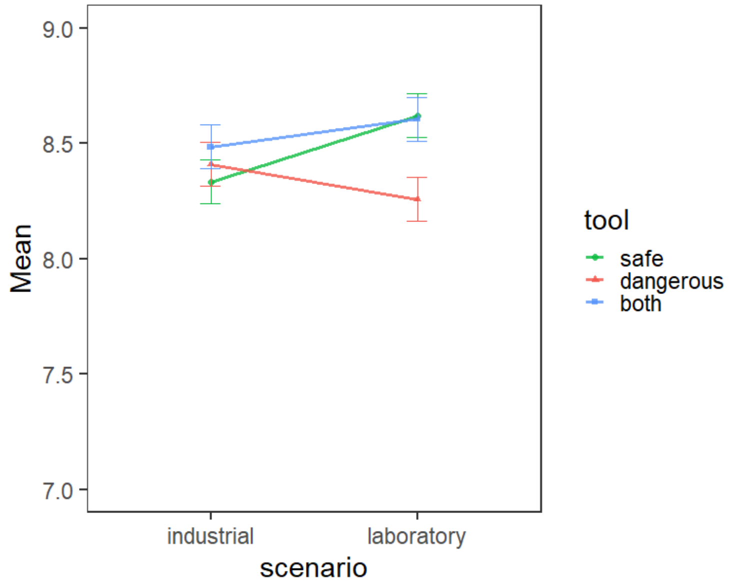

Figure 11: The two-way interaction between scenario and tool type on safety (the bars represent Fisher's least significant differences).

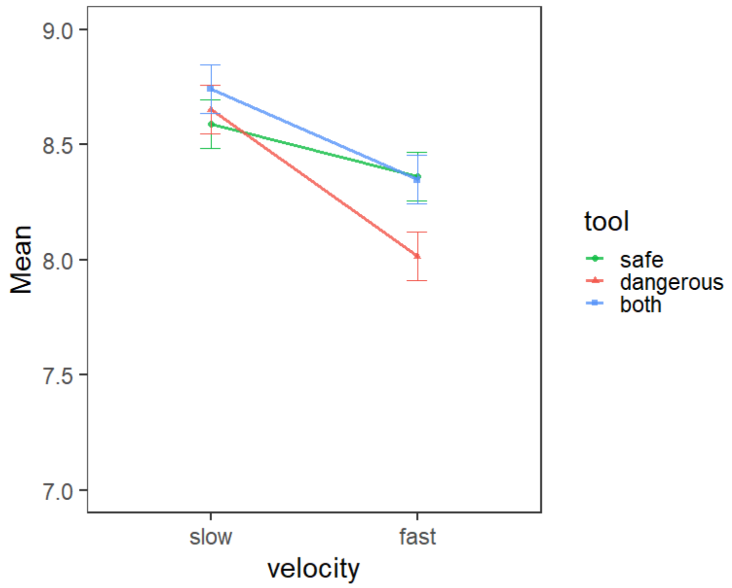

Figure 12: The two-way interaction between velocity and tool type on safety (the bars represent Fisher's least significant differences).

3.4 Intention to collaborate with the robot

Average intention to collaborate with the robot was high in all experimental conditions ($M_{tot} = 8.4$, $SD_{tot} = 1.0$). There were no statistically significant main and interaction effects of the three independent variables on intention to collaborate ratings (Table 4). However, there was again a small effect of velocity; the participants' intention to collaborate with the robot was slightly higher in the slow ($M = 8.5$, $SD = 0.8$) than in the fast ($M = 8.3$, $SD = 0.9$) velocity condition.

Table 4: Summary of a 3-way repeated measures ANOVA for the effects of scenario, velocity, and tool type on intention to collaborate with the robot.

Source of variation	SS	df	MS	F	p	η_g^2
Scenario	0.010	1	0.010	0.019	0.891	< .001
Residuals	16.823	32	0.526			
Velocity	4.040	1	4.040	3.752	0.062	0.010
Residuals	34.460	32	1.077			
Tool	1.273	2	0.636	1.347	0.267	0.003
Residuals	30.227	64	0.472			
Scenario x Velocity	0.040	1	0.040	0.153	0.698	< .001
Residuals	8.460	32	0.264			
Scenario x Tool	0.081	2	0.040	0.184	0.833	< .001
Residuals	14.086	64	0.220			
Velocity x Tool	0.505	2	0.253	0.851	0.432	0.001
Residuals	18.995	64	0.297			
Scenario x Velocity x Tool	0.384	2	0.192	0.718	0.492	0.001
Residuals	17.116	64	0.267			

η_g^2 – generalized eta squared

3.5 Qualitative data

After the experiment, participants were asked to share their observations, feelings, and experiences they had during the experiment. Their answers were analyzed using a thematic analysis approach. The main themes and corresponding subthemes are shown in Table 5. In general, participants found the experiment interesting and had positive feelings afterwards. Participants generally perceived the robot as safe and did not perceive the collaboration as dangerous. This may be (at least partly) explained by sampling bias (individuals that are more open and interested in robotics and similar topics were probably more likely to respond to our invitation and decided to participate in the experiment). Participants reported that different tools did not affect their feelings. They also stated that they did not perceive one tool as more dangerous and the other as safer. Participants expressed that in conditions where the robot was moving slowly and they had to wait for it, this elicited more negative emotions. For example, they said that by this time, they could have done the job themselves. An important factor highlighted by the participants was a quick adaptation to the collaboration with the robot. They stated that they got quickly used to the movement of the robot and the work tasks, and that they quickly recognized the robot as safe and predictable. This indicates that people get quickly used to working with a robot and perceive the collaboration as comfortable.

Table 5: Main themes and subthemes recognized in the interview after the experiment.

Main theme	Subtheme	Statement example #1	Statement example #2
General impressions	Positive experience	»Very funny.«	»It was great.«
	Interesting experience	»Very interesting experience.«	»The experiment was interesting.«
	General trust in the robot	»I felt very safe.«	»The robot seemed very safe to me.«
Effect of robot's parameters	No effect of the tool	»The tool did not affect my feelings.«	»For me, there was no effect of different tools.«
	Too slow	»When I had to wait for him, he got on my nerves.«	»It annoyed me when I had to wait for him because I could have done it on my own.«
Effect of the time	A quick adaptation to the requirements of the collaboration	»You get used to it quickly.«	»With each repetition, you become more accustomed to the robot and the course.«
	Beginning of the experiment	»I was a little uncomfortable at first.«	»At first, I was a little scared of what the robot would do.«

4 Summary of the results and conclusions

A general overview of the results shows that both of our collaborative applications (i.e., industrial and laboratory) elicited high levels of pleasure, low levels of arousal, high levels of perceived safety, and high intention to collaborate with the robot by the participants. Thus, the overall conclusion from the results of Experiment 2 is that the robot was positively received by the participants and that they generally felt safe while collaborating with the robot. This was also corroborated by the qualitative data; the participants generally expressed positive feelings after the end of the experiment and reported that they felt very safe during the experiment.

Table 6: Summary of significant main effects and interactions.

	Pleasure	Arousal	Safety	Collaboration
Scenario				
Velocity	✓	✓	✓	
Tool Type	✓	✓		
Scenario x Velocity				
Scenario x Tool Type		✓	✓	
Velocity x Tool Type	✓		✓	
Scenario x Velocity x Tool Type				

However, there was some variability in the self-report measures that could be explained by the three independent variables (Table 6). The most consistent effect was the main effect of velocity of the robot's movement; higher velocity led to slightly lower levels of pleasure and perceived safety, and higher levels of arousal.

Tool type (safe vs. dangerous vs. both) also had quite consistent effects on the outcome variables. The two dangerous tools (testing leads and a pipette) were associated with slightly lower levels of pleasure and higher levels of arousal. It is important to note that the self-reported ratings in the »both tools« conditions (i.e., the robot used a safe and a dangerous tool) did not differ from the »safe tool« condition. The »both tools« condition represented a more complex collaborative application and therefore placed a higher cognitive/attentional load on the participants. This increased mental load could deter the participants from directing their attention to the dangerous tool and consequently lead to the absence of the detrimental effect of the dangerous tool on our metrics for perceived safety and acceptance of the robot. In the observational Experiment 1 (see Deliverable 1.4), tool type had a quite larger (negative) effect on the participants' perceived safety. In Experiment 1, we used a large kitchen knife as a dangerous tool, while in Experiment 2 we used testing leads and a pipette as dangerous tools (these tools were considered dangerous because they have pointy ends). Our results therefore suggest that a tool (used by a robot) has to be recognized as directly life-threatening (e.g., weapons or objects that can be effectively used as weapons, such as a kitchen knife) to be perceived as dangerous.

Our results also showed a significant two-way interaction between tool type and velocity on pleasure and safety ratings. This interaction provided additional evidence that velocity and tool type represent the most important factors of perceived safety when collaborating with the robot, because higher velocity enhanced the effect of tool type (i.e, the dangerous tools in the fast movement conditions led to lower safety ratings) and vice versa.

The qualitative data, obtained by the post-experiment interviews, also provided an important finding – the participants almost immediately adapted to the requirements of the collaborative applications and quickly entered a relaxed state during the collaboration with the robot (especially during the most complex task that required more physical and cognitive resources). This finding emphasizes the importance of appropriate implementation of objective safety measures (e.g., proximity and force sensors on the robot), because a relaxed human will be more prone to making mistakes that could lead to injuries. In sum, the results of Experiment 2 showed that (motivated) participants quickly adapted to the collaboration with the robot and started to feel comfortable, and generally perceived the collaboration and the robot itself as safe and pleasurable.