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Collaborative Robots' Perceived Safety
CROPS

Deliverable 1.4: Experimental validation – observing the robot

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

University of Ljubljana Faculty of Electrical Engineering

Univerza v Ljubljani Filozofska fakulteta
Oddelek za psihologijo

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Contents

1 Introduction

In this document, the results of the experiment 1 (observation of 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 Deliverables 1.2 and 1.3.

2 Method

2.1 Sample

There were 30 participants in total, 12 of whom were men. The mean age of the participants was 33.1 years (min = 22; max = 57; SD = 10.8). Most participants (N = 11) had a bachelor degree, followed by participants (N = 10) with a master's degree. Five participants completed high school, two vocational high school, one participant completed technical high school and one had a PhD. The sample included 14 students, 14 employed participants, one first-time job seeker, and one unemployed participant. More than half of the participants (N = 19) 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. Three participants had some superficial experience with industrial robots, while six participants had experience with iRobot Roomba.

2.2 Independent variables – robots' parameters

We examined the influence of four independent variables on the selected self-reported and behavioural measures.

Location (see the Procedure section for a detailed description of these locations)

The tasks of the participants in Experiment 1 were to approach the robot from a distance. In the first part of the approach, they had to walk toward the robot while playing a game on a tablet and stop at the moment their feeling of safety decreased (this stopping point was designated as Comfort Zone 1). Afterwards, they stopped playing the game and had the options to hold their position, move forward or backward depending on their feeling of safety (Comfort Zone 2). So, the location variable had three levels:

- the starting position of the approach towards the robot
- Comfort Zone 1
- Comfort Zone 2

Type of tool (Figure 1):

- safe (sponge for wiping the board) and
- dangerous (kitchen knife).

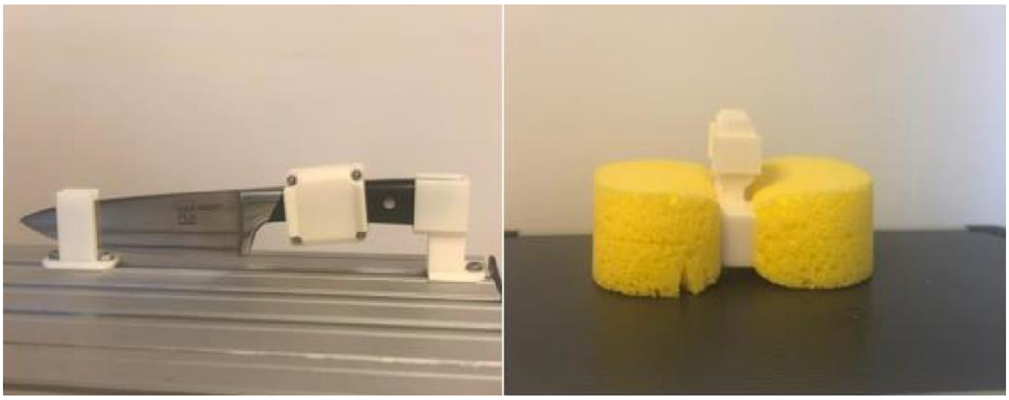

Figure 1: Dangerous and safe tool with harnesses ensuring a safe and firm grip.

Robot velocity:

- slow (0.3 m/s) and
- fast (1 m/s).

Type of robot movement:

- linear forward/backwards (FB, Figure 2),
- linear left/right (LR, Figure 3),
- linear up/down (UD, Figure 4),
- circular forward/backwards (crcFB, Figure 5),
- circular left/right (crcLR, Figure 6) and
- random movements (RAND, Figure 7), which presents a combination of the other five movements.

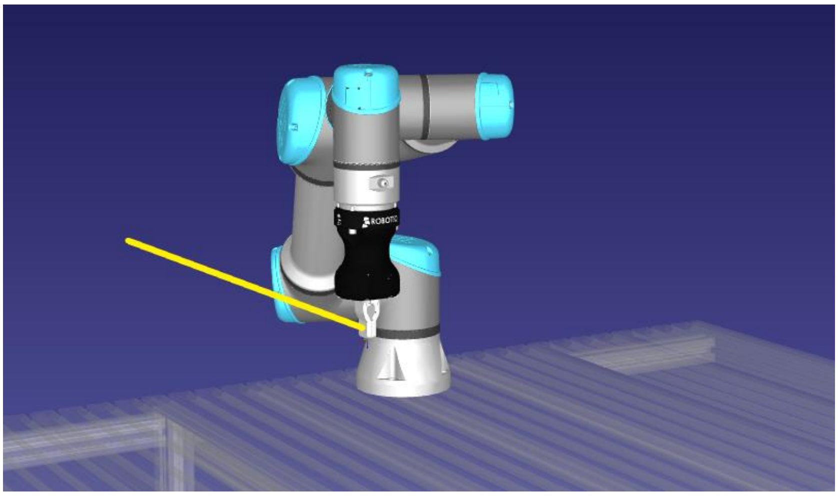

Figure 2: Linear forward/backwards (FB) movement. The yellow line presents the trajectory of the movement of the robot.

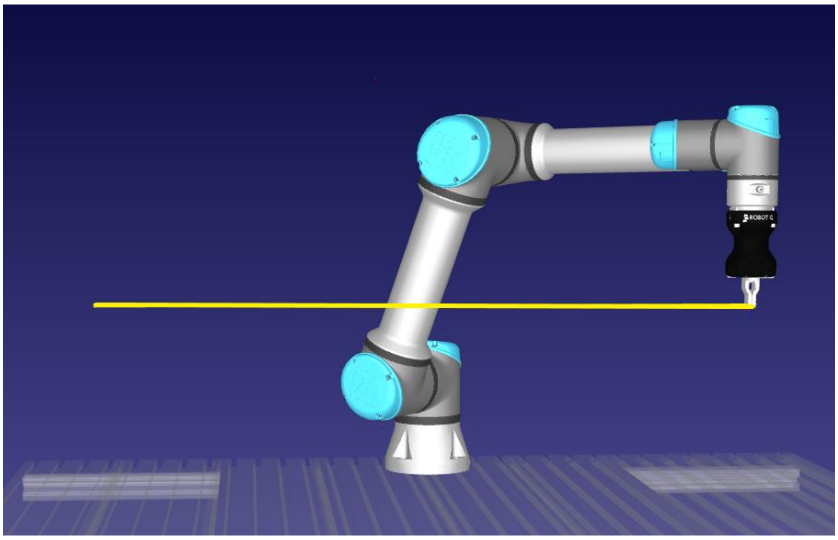

Figure 3: Linear left/right (LR) movement. The yellow line presents the trajectory of the movement of the robot.

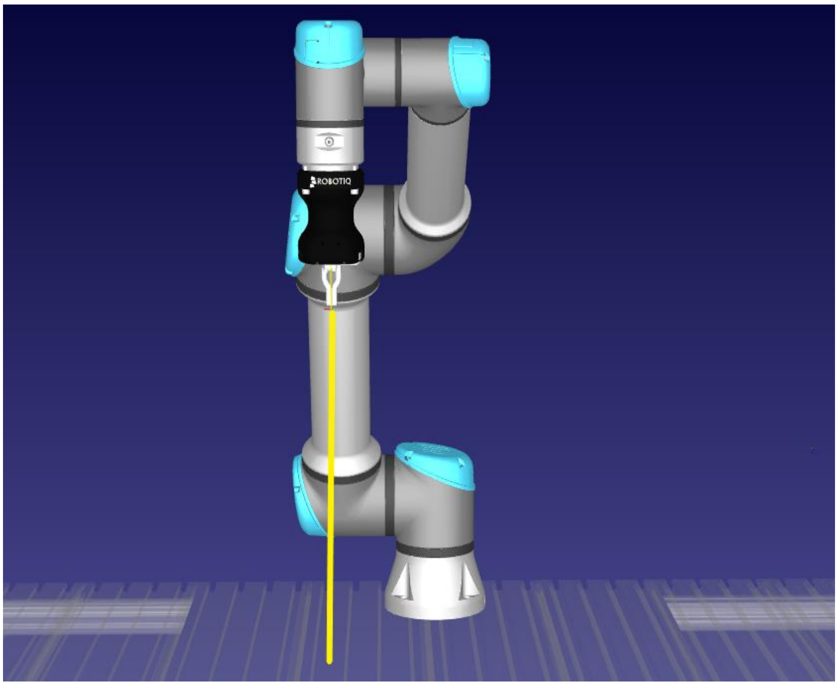

Figure 4: Linear up/down (UD) movement. The yellow line presents the trajectory of the movement of the robot.

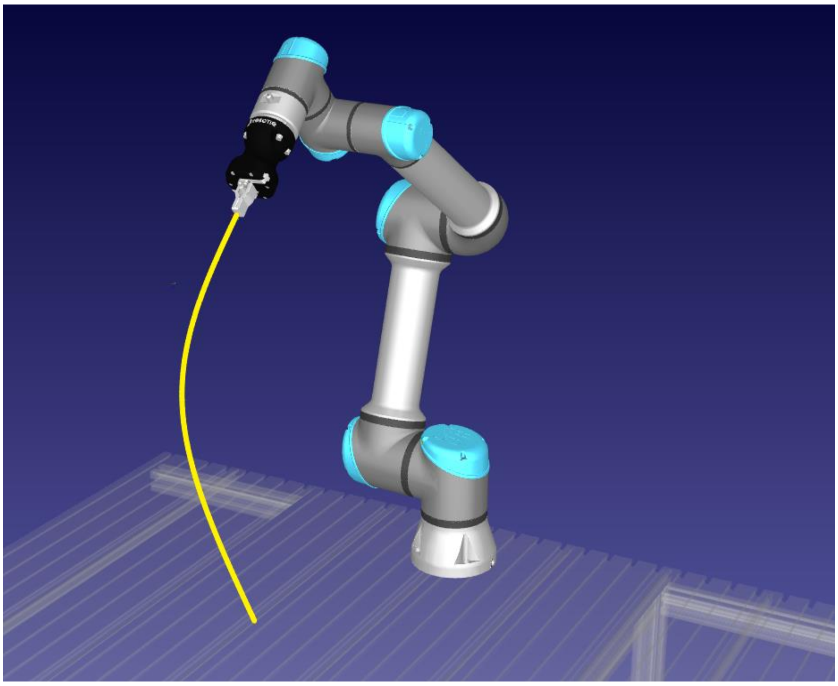

Figure 5: Circular forward/backwards (crcFB) movement. The yellow line presents the trajectory of the movement of the robot.

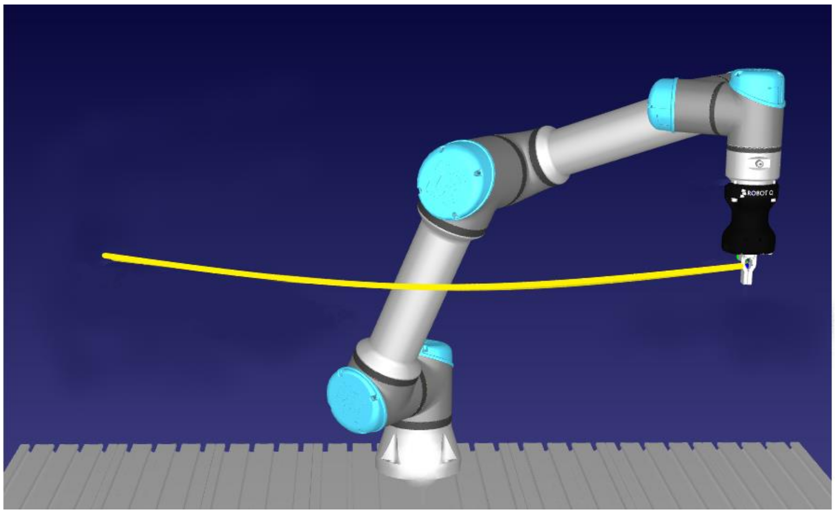

Figure 6: Circular left/right (crcLR) movement. The yellow line presents the trajectory of the movement of the robot.

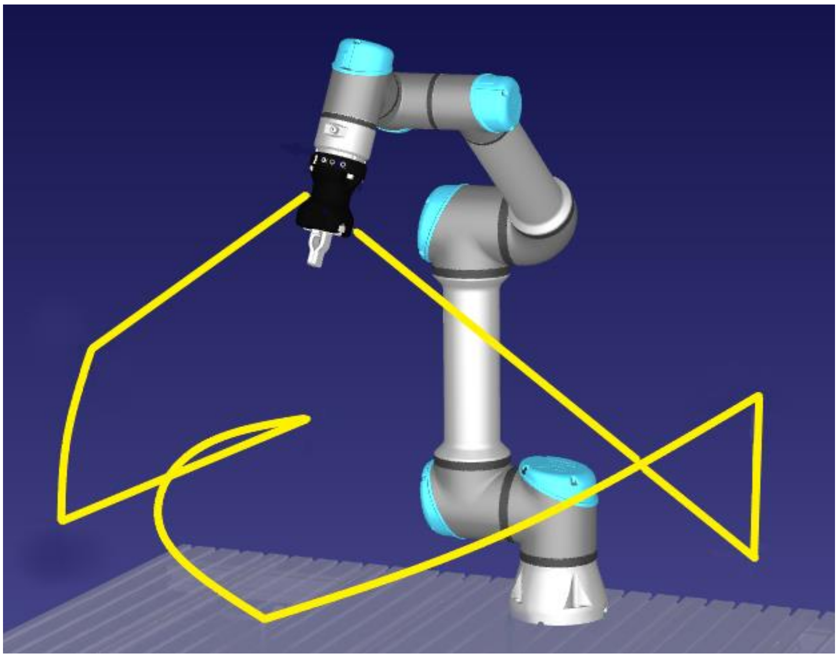

Figure 7: Random (RAND) movements which present a combination of the linear and circular movements. The yellow line presents the trajectory of the movement of the robot.

With such a research plan, we obtained 72 (3 x 2 x 2 x 6) experimental conditions. Every participant was exposed to each of the conditions only once, and the order of the conditions (defined by tool type, velocity, and movement type) within each participant was randomized.

2.3 Dependent variables

Variables measured in the Experiment 1 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 8 for pleasure and Figure 9 for arousal) that best represented how they felt when observing the robot. For each condition, they gave three responses at three different locations relative to the robot: at the starting point of their approach to the robot (Pleasure 1, Arousal 1), at Comfort zone 1 (Pleasure 2, Arousal 2), and at Comfort zone 2 (Pleasure 3, Arousal 3). See the Procedure section for details about these three locations.

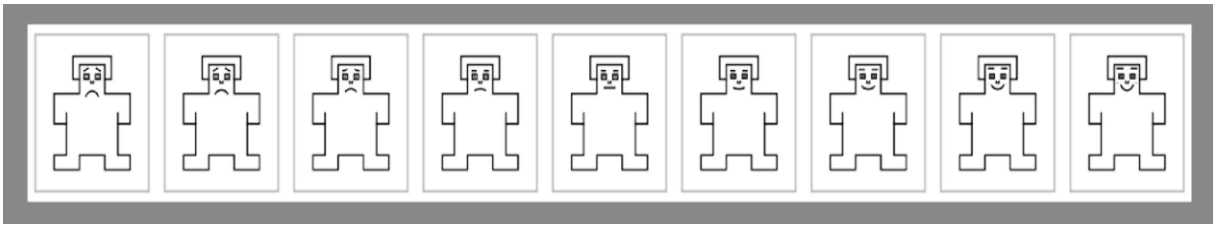

Figure 8: The 9-point Self-Assessment Manikins for measuring pleasure.

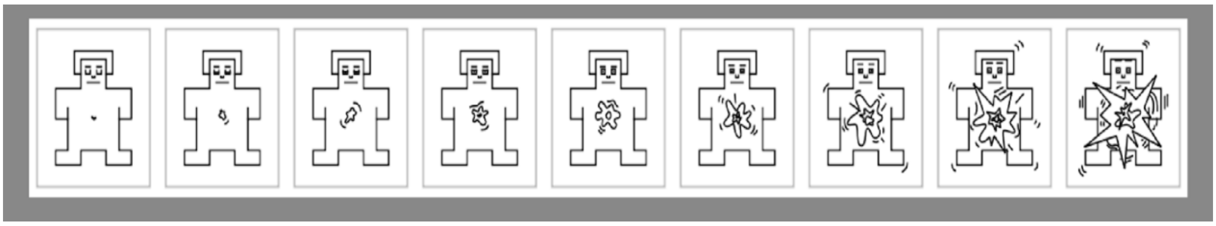

Figure 9: The 9-point Self-Assessment Manikins for measuring arousal.

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

On each trial/approach to the robot, participants answered 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 with a robot? « on a 9-point scale (1 – not at all, 9 – most certainly). The participants again provided their answers at three different locations relative to the robotic arm, i.e., the starting point of the approach and Comfort Zones 1 and 2.

Mean deviation of the car from the center of the road in the car driving simulation game.

A simple car driving game was included in the experiment to simulate the divided attention required by workers to complete other tasks in the presence of robots. The game is intuitive to play, but still requires substantial attention from the player during the game. The car has a constant forward velocity. The steering is implemented by tilting the tablet sideways: tilting it to the left moved the car to the left and vice-versa. The participant had to keep the car as close to the centre of the road as possible. While playing the game, the deviations from the middle of the road were calculated and recorded. Although this measure (average deviation in each condition) also depends on the participant's motor abilities and previous experience with such games, we used this variable as an approximate measure of the participants attention to the game (or inattention to the robot).

Comfort Zone 1 and Comfort Zone 2

Comfort Zone 1 (CZ1) represents the distance to the robot at which the participant still feels safe in the divided attention condition, while Comfort Zone 2 (CZ2) represents the distance between the participant and the robot when the participant can focus his or her full attention on the robot. Both comfort zones were measured in millimetres. See the Procedure section for a detailed description of both CZs.

The course of the experiment is presented below in terms of participant's actions and measured variables (marked in bold) and in Figure 10.

1. Observing the robot at the distance.
2. **Pleasure 1, Arousal 1, Safety 1, Collaboration 1.**
3. Approaching the robot → **mean deviation**.
4. Stopping → **Comfort Zone 1** → **Pleasure 2, Arousal 2, Safety 2, Collaboration 2**.
5. Stepping further toward the robot, staying in the same place, or stepping back → **Comfort Zone 2** → **Pleasure 3, Arousal 3, Safety 3, Collaboration 3**.

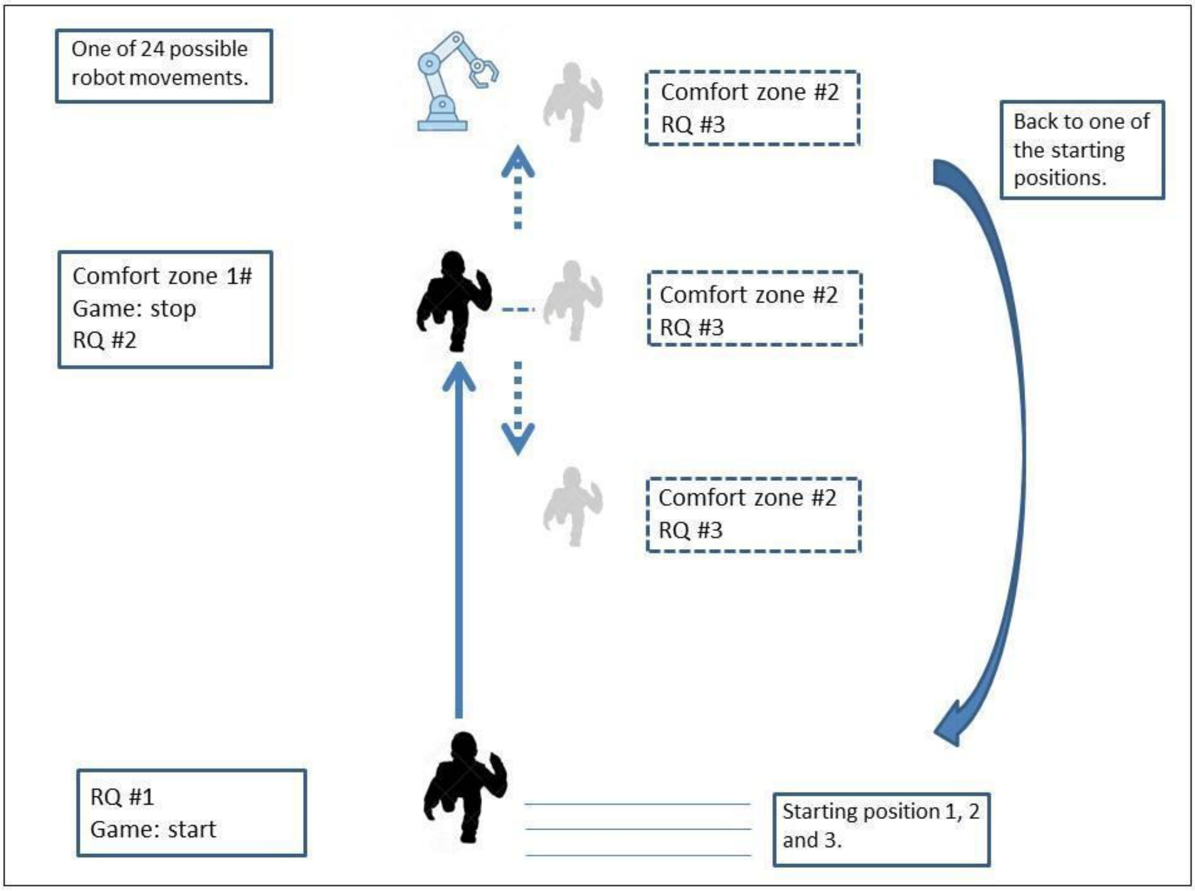

Figure 10: The graphical representation of the procedure of Experiment 1.

2.4 Procedure of Experiment 1

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 5 to 10 minutes.

Participants were then introduced to a robot at a distance (6.5 m from the robot) at which we assumed everyone felt safe. After the robot started its first movement, they responded to the experimental questions for the first time (self-reported research questionnaire (RQ) during the experiment). The initial position is presented in Figures 10 and 11. After responding to the RQ items, the game (driving a car) appeared on the tablet. Participants started to approach the robot and at the same time play the game, i.e., drive the car on the road by tilting the tablet sideways, making sure the car stays as close to the middle of the road as possible (Figure 12). The game represented an additional task (besides moving towards the robot). This served as a simulation of a real work setting, in which employees are performing some other tasks in the vicinity of a robot. They approached the robot until they still felt completely safe and then stopped when their perceived safety decreased. After stopping and looking at the robot (the participants also marked the end of their first approach by pressing the corresponding button on the tablet; this action also stopped the game), they then again responded to the RQ items (Figure 13). The participants were presented with their answers, given at the starting position of the trial, and only had to change the answers where there has been a change since the initial state. The distance of the participant to the robot, measured by the laser sensor at the robot, is designated as Comfort Zone 1. Then, if the participant wanted and/or felt safe/unsafe, they had the opportunity to (a) get closer to the robot, (b) stay where they are, or (c) move further away from the robot. The distance at which the participant stopped represents their Comfort Zone 2 (Figure 14). At this point, the experimental questions were again displayed on the tablet with the values they gave at the comfort zone 1 and changed only those ratings where their feelings changed. Comfort Zone 1 represents the distance to the robot at which the participant still felt safe in the divided attention condition, while Comfort Zone 2 represents the distance between the participant and the robot when the participant could focus his full attention on the robot. Participants were then asked to go back to one of the three starting points: 1 (5.5 m away), 2 (6 m away) or 3 (6.5 m away) that were randomly chosen. The three starting points were used to prevent the participants from using strategies (e.g., always stopping after a certain number of steps) that could lead to unwanted systematic effects. Then they continued with the next trial (the robotic arm started with its next movement). Participants had to repeat this multiphase approach towards the robot for each of the 24 experimental conditions, defined by the other three independent variables (i.e., two tools x two robot movement velocities x six types of robot movements). The sequence of experimental conditions was random for each participant. Before the experiment, each participant was given three practice trials to familiarise with the procedure. The results of the practice trials were not recorded.

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. The executive researchers thanked the participants for their time and cooperation and accompanied them from the faculty.

Figure 11: Participant is observing the robot and responding to RQ at a distance.

Figure 12: On the left side a participant approaching the robot while playing the game is presented. Screenshot of the game is presented on the right side.

Figure 13: Participant is standing in his comfort zone 1 and responding to the RQ for the second time.

Figure 14: Participant is standing in her comfort zone 2 and responding to the RQ for the third time.

3 Results of Experiment 1

3.1 3.1 Mean deviation (car driving simulation game)

A three-way repeated measures ANOVA was run to examine the effects of the robot's tool, velocity, and movement on the mean deviation. None of the main and interaction effects were statistically significant (Table 1). The absence of any salient effect can also be seen in Figure 15, depicting the three-way interaction between the independent variables.

Table 1: Summary of a 3-way repeated measures ANOVA results on deviation as a function of tool, velocity, and movement of the robot

Source of variation	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Tool	0.004	1.00	0.004	0.22	0.642	0.01
Tool (error)	0.540	29.00	0.019			
Velocity	0.017	1.00	0.017	1.88	0.181	0.06
Velocity (error)	0.267	29.00	0.009			
Movement	0.146	5.00	0.029	2.31	0.047	0.07
Movement (error)	1.830	145.00	0.013			
Tool x velocity	0.002	1.00	0.002	0.14	0.708	0.00
Tool x velocity (error)	0.387	29.00	0.013			
Tool x movement #	0.057	3.63	0.016	0.74	0.554	0.02
Tool x movement (error)	2.231	105.40	0.021			
Velocity x movement #	0.032	3.03	0.011	0.60	0.617	0.02
Velocity x movement (error)	1.550	88.01	0.018			
Tool x velocity x movement	0.084	5.00	0.017	1.25	0.287	0.04
Tool x velocity x movement (error)	1.942	145.00	0.013			

Note. SS = Sum of squares, df = degrees of freedom, MS = mean square, η_p^2 = partial eta squared
Mauchly's test indicated that the assumption of sphericity has been violated for these effects, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity.

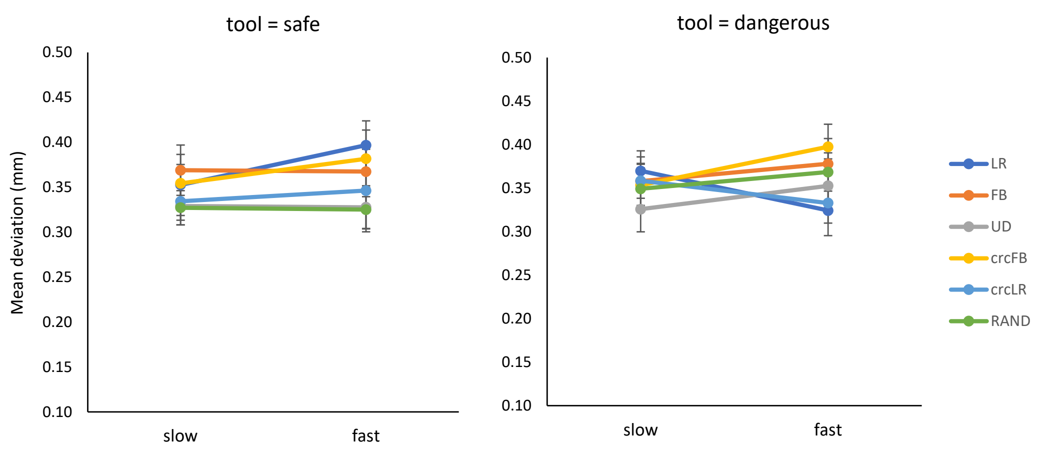

Figure 15: Mean deviation as a function of tool, velocity, and movement of the robot (the bars represent the standard errors of the means).

3.2 Comfort zones 1 and 2

A three-way repeated measures ANOVA was run to examine the effects of tool, velocity, and movement of the robot on Comfort Zone 1. There were statistically significant main effects of tool, velocity, and movement of the robot. The main effects of tool and velocity were by far the largest effects. Pairwise comparisons with the Sidak correction revealed that the comfort zone 1 was significantly shorter (i.e., the participants came closer to the robot) when the tool used was safe and when the velocity of the robot was slow. In addition, the participants came closest to the robot when the movements were UD, LR, and crcLR, so CZ1 was greater when the movements were FB, crcFB, and RAND. There was no statistically significant three-way interaction between tool, velocity, and movement of the robot as indicated in the upper part of Table 2. However, statistically significant, albeit weak two-way interactions were observed between tool and movement of the robot and between velocity and movement of the robot, but not between tool and velocity of the robot. Specifically, the previously described effect of the tool (i.e., safe vs. dangerous) was largest for the FB, crcFB, and RAND movements and it was smallest for the UD and crcLR movements (Figure 16). The effect of velocity (i.e., slow vs. fast) was largest for the LR and FB movements and it was smallest for the RAND movement (Figure 16).

Regarding Comfort Zone 2, all main effects were statistically significant (the lower part of Table 2), with tool type and velocity again having the largest effects. Pairwise comparisons revealed that the comfort zone 2 distance was significantly shorter (i.e., the participant came closer to the robot) when the tool used was safe and when the velocity of the robot was slow. Participants also came closest to the robot when the movements were UD, LR, and crcLR. There was no statistically significant three-way interaction between tool, velocity, and movement of the robot as presented in Table 2. However, statistically significant two-way interaction between velocity and movement was observed. The effect of velocity (i.e., slow vs. fast) was largest for the FB and LR movements and it was smallest for the crcFB movement (Figure 17).

Table 2: Summary of a 3-way repeated measures ANOVA results on Comfort Zones 1 & 2 as a function of tool, velocity, and movement of the robot.

Source of variation	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Comfort zone 1						
Tool	13110932.33	1.00	13110932.33	52.84	0.000	0.65
Tool (error)	7195546.96	29.00	248122.31			
Velocity	2748987.67	1.00	2748987.67	23.57	0.000	0.45
Velocity (error)	3382576.96	29.00	116640.58			
Movement #	1517017.11	3.65	415164.92	7.69	0.000	0.21
Movement (error)	5720864.52	105.97	53987.58			
Tool x velocity	14302.33	1.00	14302.33	0.62	0.436	0.02
Tool x velocity (error)	665136.46	29.00	22935.74			
Tool x movement #	414079.41	5.00	82815.88	2.56	0.030	0.08
Tool x movement (error)	4688831.05	145.00	32336.77			
Velocity x movement #	484572.71	3.24	149361.29	2.78	0.041	0.09
Velocity x movement (error)	5051827.42	94.08	53694.48			
Tool x velocity x movement #	21513.37	3.76	5721.88	0.09	0.983	0.00
Tool x velocity x movement (error)	7186907.58	109.04	65913.54			
Comfort zone 2						
Tool	14379818.76	1.00	14379818.76	41.99	0.000	0.59
Tool (error)	9932256.99	29.00	342491.62			
Velocity	2548266.05	1.00	2548266.05	19.88	0.000	0.41
Velocity (error)	3718224.20	29.00	128214.63			
Movement #	2561371.29	2.26	1134292.94	7.80	0.001	0.21
Movement (error)	9524858.79	65.49	145449.84			
Tool x velocity	59659.61	1.00	59659.61	0.92	0.344	0.03
Tool x velocity (error)	1872693.98	29.00	64575.65			
Tool x movement #	219516.99	1.96	111877.92	0.65	0.523	0.02
Tool x movement (error)	9800094.76	56.90	172229.89			
Velocity x movement #	1131372.57	1.90	596976.59	4.20	0.022	0.13
Velocity x movement (error)	7812524.68	54.96	142149.41			
Tool x velocity x movement #	192187.98	2.40	80054.78	0.63	0.564	0.02
Tool x velocity x movement (error)	8844350.94	69.62	127036.64			

Note. SS = Sums of squares, df = degrees of freedom, MS = mean square, η_p^2 = partial eta squared
Mauchly's test indicated that the assumption of sphericity has been violated for these effects, therefore degrees of freedom were corrected using Greenhouse-Geisser correction.

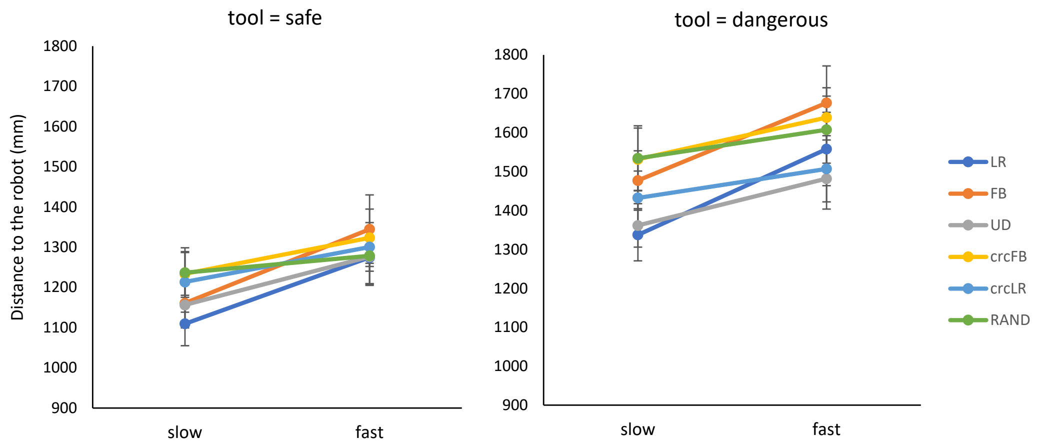

Figure 16: Comfort zone 1 as a function of tool, velocity, and movement of the robot (the bars represent the standard errors of the means).

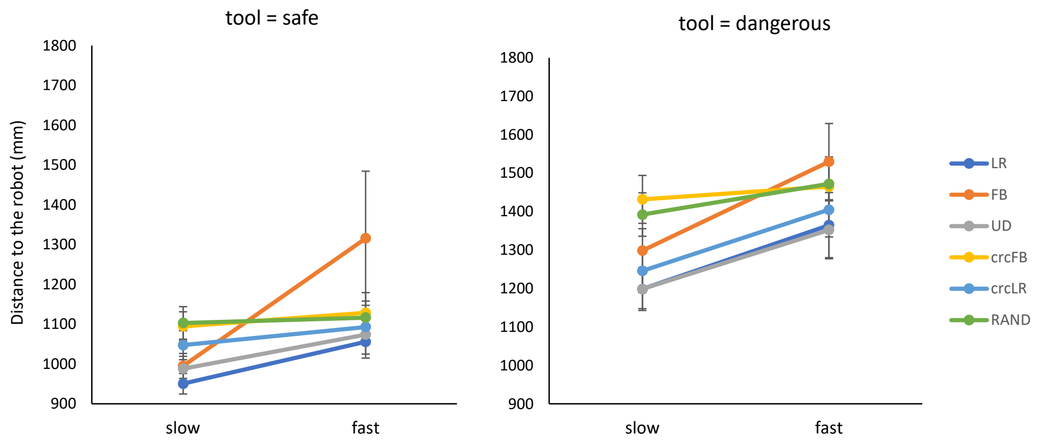

Figure 17: Comfort zone 2 as a function of tool, velocity, and movement of the robot (the bars represent the standard errors of the means).

3.3 Pleasure

A four-way repeated measures ANOVA was run to examine the effects of location (starting position, CZ1, CZ2), tool (safe, dangerous), velocity (slow, fast), and movement (FB, LR, UD, crcFB, crcLR, and RAND) on the perceived level of pleasure. All four main effects were significant (Table 3). By far the strongest was the effect of the tool; the participants reported significantly higher levels of pleasure when the tool was safe (M = 7.7, SD = 1.1) compared to when the tool was dangerous (M = 6.0, SD = 1.7). There was also a strong effect of the velocity of the robot; the participants reported higher levels of pleasure when the robot was moving slow (M = 7.2, SD = 1.2) and lower levels of pleasure when the robot was moving fast (M = 6.4, SD = 1.5). The effect of movement type is shown in Figure 18. Participants reported highest levels of pleasure with LR, UD, and crcLR movements. The effect of location is shown in Figure 19. The highest pleasure was at the starting point and the lowest at CZ2.

Table 3: Summary of a 4-way repeated measures ANOVA results on pleasure as a function of location, tool, velocity, and movement of the robot.

Source of variation	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Location #	59.884	1.304	45.913	12.097	0.001	0.29
Location (error)	143.56	37.825	3.795			
Tool	1594.785	1	1594.785	61.314	0.000	0.68
Tool (error)	754.298	29	26.01			
Velocity	344.002	1	344.002	22.203	0.000	0.43
Velocity (error)	449.304	29	15.493			
Movement #	57.27	3.931	14.569	3.004	0.022	0.09
Movement (error)	552.924	114	4.85			
Location x Tool #	22.756	1.201	18.945	7.193	0.008	0.20
Location x Tool (error)	91.744	34.835	2.634			
Location x Velocity #	1.006	1.607	0.626	1.077	0.337	0.04
Location x Velocity (error)	27.105	46.597	0.582			
Tool x Velocity	0.313	1	0.313	0.058	0.811	0.00
Tool x Velocity (error)	156.493	29	5.396			
Location x Tool x Velocity #	3.545	1.762	2.012	11.341	0.000	0.28
Location x Tool x Velocity (error)	9.066	51.105	0.177			
Location x Movement #	4.51	4.817	0.936	1.359	0.245	0.05
Location x Movement (error)	96.212	139.698	0.689			
Tool x Movement #	43.948	3.783	11.616	2.895	0.028	0.09
Tool x Movement (error)	440.302	109.721	4.013			
Location x Tool x Movement #	7.794	6.382	1.221	2.135	0.048	0.07
Location x Tool x Movement (error)	105.873	185.068	0.572			
Velocity x Movement #	39.098	4.229	9.246	3.043	0.018	0.10
Velocity x Movement (error)	372.596	122.632	3.038			
Location x Velocity x Movement #	4.477	4.917	0.911	1.15	0.337	0.04
Location x Velocity x Movement (error)	112.912	142.584	0.792			
Tool x Velocity x Movement #	18.82	4.206	4.474	1.768	0.136	0.06
Tool x Velocity x Movement (error)	308.707	121.988	2.531			
Location x Tool x Velocity x Movement #	3.738	4.354	0.858	1.005	0.411	0.03
Location x Tool x Velocity x Movement (error)	107.818	126.275	0.854			

Note. SS = Sums of squares, df = degrees of freedom, MS = mean square, η_p^2 = partial eta squared
Mauchly's test indicated that the assumption of sphericity has been violated for these effects, therefore degrees of freedom were corrected using Greenhouse-Geisser correction.

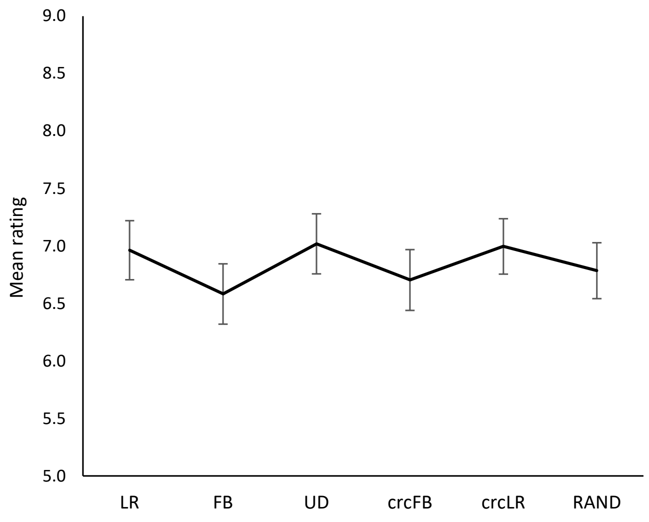

Figure 18: The main effect of movement type on pleasure (the bars represent the standard errors of the means).

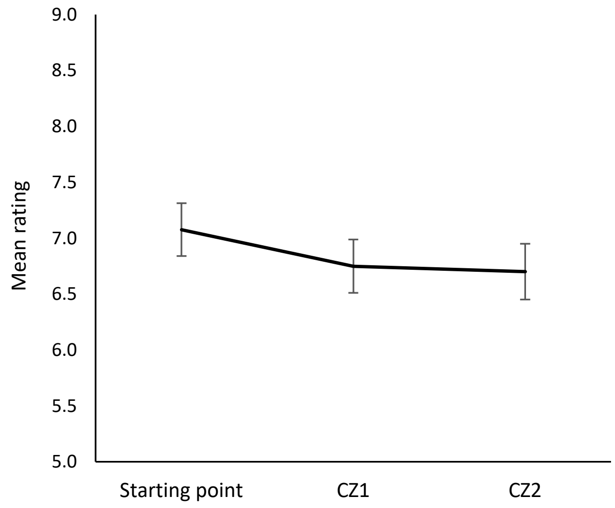

Figure 19: The main effect of the location on pleasure (the bars represent the standard errors of the means).

Additionally, we found a small but significant two-way interaction between tool and movement (Table 3). Effect of the tool was the largest in combination with FB in RAND movement. Another weak interaction was between velocity and movement. Effect of the velocity was the largest in combination with LR and FB movements.

A significant three-way interaction between location, tool and velocity was found. As seen in Figure 20, the significant two-way interaction between the tool and location (effect of the tool was larger when the participants were closer to the robot (CZ1 and CZ2) was less pronounced in the fast movement condition; specifically, the difference in pleasure at the starting point was slightly smaller in slow compared to the fast movement condition. However, both interaction effects were rather weak, as shown in Table 3.

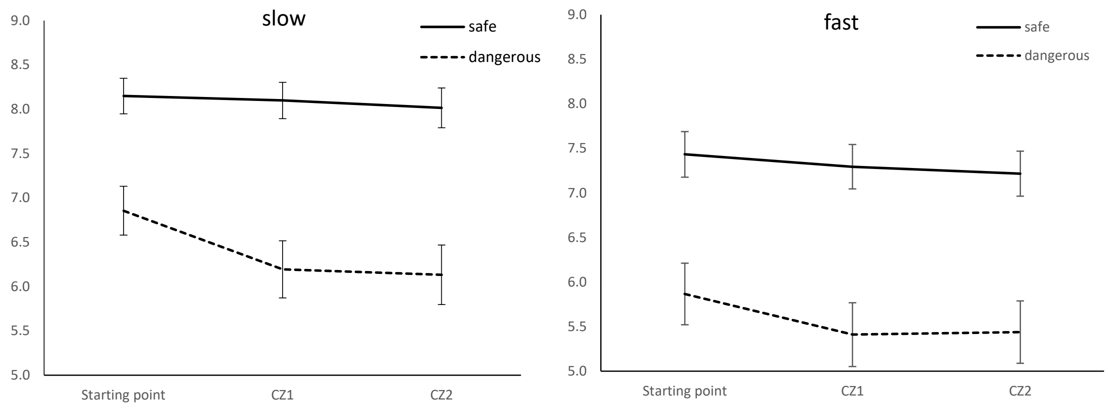

Figure 20: Three-way interaction between velocity, tool type and location on pleasure (the bars represent the standard errors of the means).

3.4 Arousal

A four-way ANOVA (Table 4) was run to examine the effects of our independent variables on arousal. All four main effects were significant and very large (with the exception of movement type). Participants reported higher levels of arousal when the robot was using a knife (*M* = 3.5, *SD* = 1.5) compared to when it was using a soft sponge (*M* = 2.3, *SD* = 1.2). Participants were more aroused if the robot was moving fast (*M* = 2.5, *SD* = 1.2) compared to when it was moving slow (*M* = 3.2, *SD* = 1.5). The main effect of the location is shown in Figure 21. Participants' arousal was higher when they were closer to the robot. The main effect of movement type is shown in Figure 22. Participants reported highest arousal with FB movement, followed by LR and RAND movements.

Table 4: Summary of a 4-way repeated measures ANOVA results on arousal as a function of location, tool, velocity, and movement of the robot.

Source of variation	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Location #	173.656	1.407	123.462	21.745	0.000	0.43
Location (error)	231.594	40.79	5.678			
Tool	798.134	1	798.134	56.72	0.000	0.66
Tool (error)	408.075	29	14.072			
Velocity	251.467	1	251.467	18.297	0.000	0.39
Velocity (error)	398.575	29	13.744			
Movement #	43.275	4.384	9.871	3.15	0.014	0.10
Movement (error)	398.434	127.134	3.134			
Location x Tool #	17.118	1.43	11.972	6.169	0.009	0.18
Location x Tool (error)	80.466	41.465	1.941			
Location x Velocity #	0.129	1.949	0.066	0.166	0.842	0.01
Location x Velocity (error)	22.455	56.517	0.397			
Tool x Velocity	0.856	1	0.856	0.206	0.653	0.01
Tool x Velocity (error)	120.352	29	4.15			
Location x Tool x Velocity #	1.056	1.413	0.748	1.624	0.213	0.05
Location x Tool x Velocity (error)	18.86	40.986	0.46			
Location x Movement #	2.832	5.342	0.53	0.802	0.557	0.03
Location x Movement (error)	102.418	154.926	0.661			
Tool x Movement #	33.463	4.017	8.331	3.256	0.014	0.10
Tool x Movement (error)	298.078	116.484	2.559			
Location x Tool x Movement #	7.494	5.483	1.367	1.851	0.099	0.06
Location x Tool x Movement (error)	117.423	159.019	0.738			
Velocity x Movement #	21.052	4.148	5.075	1.902	0.112	0.06
Velocity x Movement (error)	320.989	120.302	2.668			
Location x Velocity x Movement #	1.46	3.439	0.425	0.333	0.828	0.01
Location x Velocity x Movement (error)	127.123	99.734	1.275			
Tool x Velocity x Movement #	11.53	4.188	2.753	1.183	0.322	0.04
Tool x Velocity x Movement (error)	282.678	121.446	2.328			
Location x Tool x Velocity x Movement #	2.966	4.834	0.613	0.804	0.545	0.03
Location x Tool x Velocity x Movement (error)	106.951	140.195	0.763			

Note. SS = Sums of squares, df = degrees of freedom, MS = mean square, η_p^2 = partial eta squared
Mauchly's test indicated that the assumption of sphericity has been violated for these effects, therefore degrees of freedom were corrected using Greenhouse-Geisser correction.

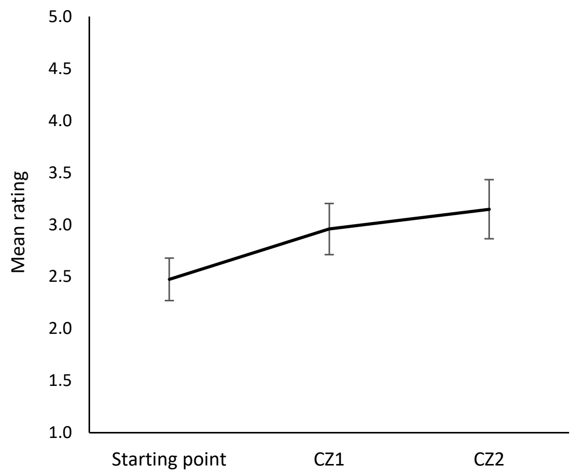

Figure 21: The main effect of the location on arousal (the bars represent the standard errors of the means).

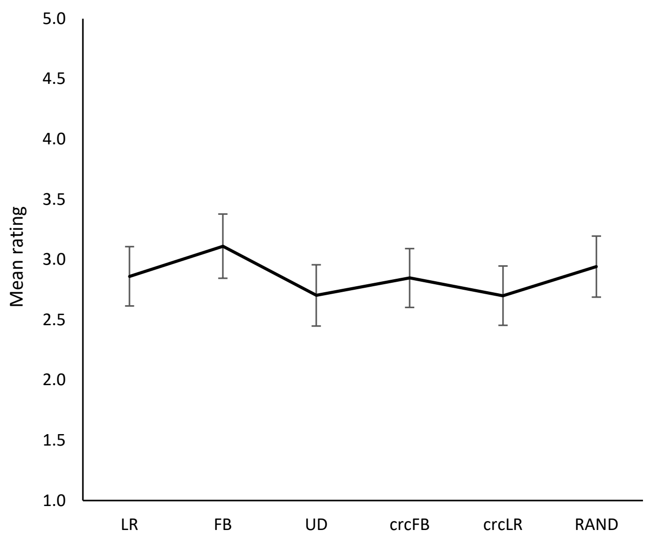

Figure 22: The main effect of movement type on arousal (the bars represent the standard errors of the means).

There was a small but significant two-way interaction between the tool type and location (Figure 23). The difference between safe and dangerous tools was smallest at the starting point and largest at a CZ1. There was also a significant two-way interaction between the tool and movement type, but the effect was relatively small. The difference in arousal between fast and slow movement l was the largest in with RAND, FB, and crcFB movements. As already stated, both of these interactions were weak.

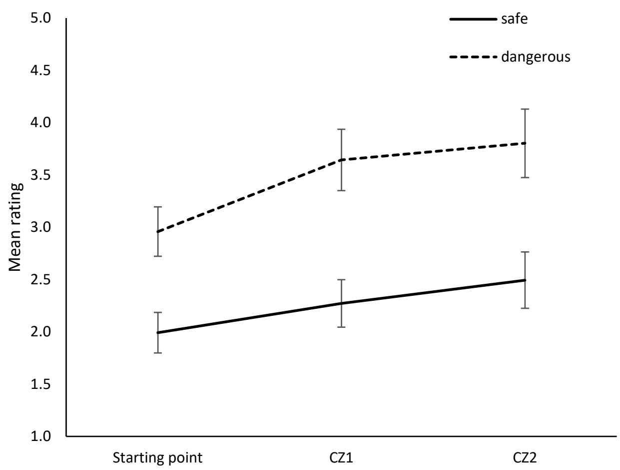

Figure 23: Two-way interaction between tool and location on arousal (the bars represent the standard errors of the means).

3.5 Perceived safety

Perceived safety is one of the key elements of successful human-robot interaction, and that is why we were interested in how location of the participants, tool type, velocity, and type of robot's movement affect safety perception. The main effects of tool, velocity, and movement type were statistically significant (Table 5). Similar as stated with pleasure and arousal, participants reported higher levels of safety when the robot was using a safe tool (M = 7.9, SD = 1.1) compared to a dangerous tool (M = 6.4, SD = 1.8) and when the robot was moving slow (M = 7.6, SD = 1.2) compared to moving fast (M = 6.7, SD = 1.6). There was also the main effect of movement of the robot, as shown in Figure 24. Participants reported highest perceived safety with LR, UD, and crcLR movements. The location did not have a significant effect on perceived safety.

Table 5: Summary of a 4-way repeated measures ANOVA results on perceived safety as a function of location, tool, velocity, and movement of the robot.

Source of variation	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Location #	11.669	1.14	10.239	2.88	0.095	0.09
Location (error)	117.525	33.05	3.556			
Tool	1297.35	1	1297.35	37.138	0.000	0.56
Tool (error)	1013.067	29	34.933			
Velocity	453.75	1	453.75	31.952	0.000	0.52
Velocity (error)	411.833	29	14.201			
Movement #	80.267	3.449	23.271	3.666	0.011	0.11
Movement (error)	634.928	100.029	6.347			
Location x Tool #	6.103	1.323	4.613	4.942	0.023	0.15
Location x Tool (error)	35.814	38.368	0.933			
Location x Velocity #	1.303	1.797	0.725	2.995	0.064	0.09
Location x Velocity (error)	12.614	52.101	0.242			
Tool x Velocity	10.417	1	10.417	2.344	0.137	0.08
Tool x Velocity (error)	128.889	29	4.444			
Location x Tool x Velocity #	0.436	1.422	0.307	0.803	0.416	0.03
Location x Tool x Velocity (error)	15.758	41.242	0.382			
Location x Movement #	3.114	5.327	0.585	1.41	0.220	0.05
Location x Movement (error)	64.025	154.49	0.414			
Tool x Movement #	45.822	3.821	11.993	2.401	0.057	0.08
Tool x Movement (error)	553.428	110.804	4.995			
Location x Tool x Movement #	2.192	5.679	0.386	1.038	0.401	0.04
Location x Tool x Movement (error)	61.225	164.703	0.372			
Velocity x Movement #	52.367	3.494	14.986	3.359	0.017	0.10
Velocity x Movement (error)	452.05	101.338	4.461			
Location x Velocity x Movement #	1.447	6.06	0.239	0.692	0.658	0.02
Location x Velocity x Movement (error)	60.636	175.742	0.345			
Tool x Velocity x Movement #	30.633	2.949	10.387	2.095	0.108	0.07
Tool x Velocity x Movement (error)	424.061	85.523	4.958			
Location x Tool x Velocity x Movement #	1.514	5.706	0.265	0.766	0.591	0.03
Location x Tool x Velocity x Movement (error)	57.292	165.467	0.346			

Note. SS = Sums of squares, df = degrees of freedom, MS = mean square, η_p^2 = partial eta squared # Mauchly's test indicated that the assumption of sphericity has been violated for these effects, therefore degrees of freedom were corrected using Greenhouse-Geisser correction

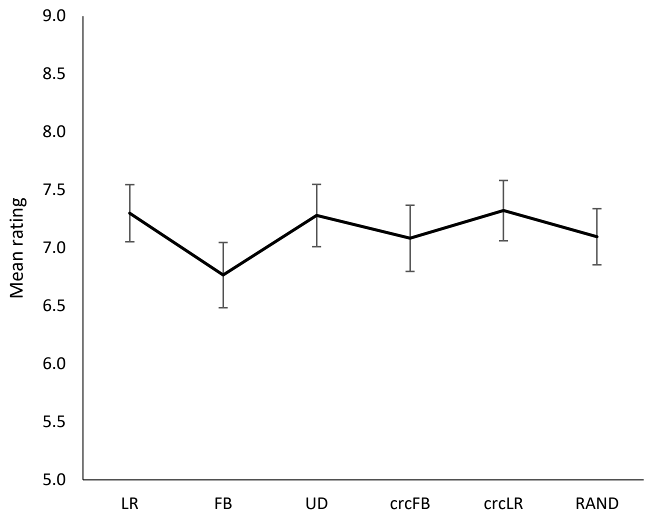

Figure 24: The main effect of movement type on perceived safety (the bars represent the standard errors of the means).

A significant two-way interaction was found between location and tool on perceived safety (Figure 25). There was a larger difference in perceived safety between safe and dangerous tool at CZ1 and CZ2 compared to starting point A second significant (but smaller) interaction was observed between velocity and movement type on perceived safety. There was a larger difference in the perception of safety between slow and fast movement in the condition of FB movement compared to crcFB and crcLR movements. Both interaction effects were again relatively small.

There were three significant two-way interactions: between location and tool, between location and velocity, and between velocity and movement. It is worth mentioning that these interactions were rather weak, especially compared to the main effects. There was a larger difference in the intention to collaborate between fast and slow movements in the condition of FB and LR movements compared to UD and crcFB movements. The interaction between location and tool type is shown in Figure 27. The interaction has the same pattern as with arousal, pleasure, and perceived safety. There was a smaller difference in reported intention to collaborate between safe and dangerous tool in the starting point condition. Interaction between location and velocity is shown in Figure 28. There was a larger difference in reported intention to collaborate between fast and slow movements in the starting point condition compared to CZ1 and CZ2.

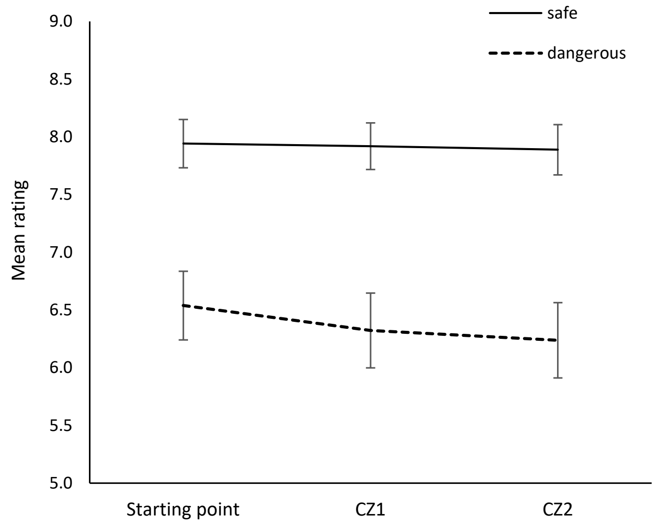

Figure 25: Interaction between location and tool on the perceived safety (the bars represent the standard errors of the means).

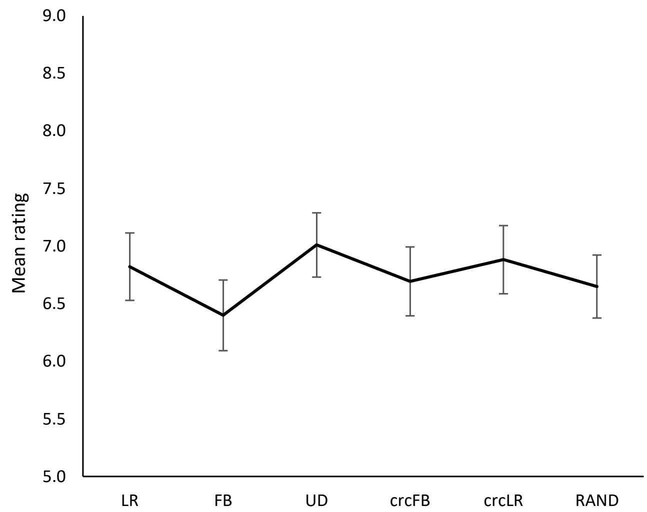

Figure 26: The main effect of movement type on intention to collaborate (the bars represent the standard errors of the means).

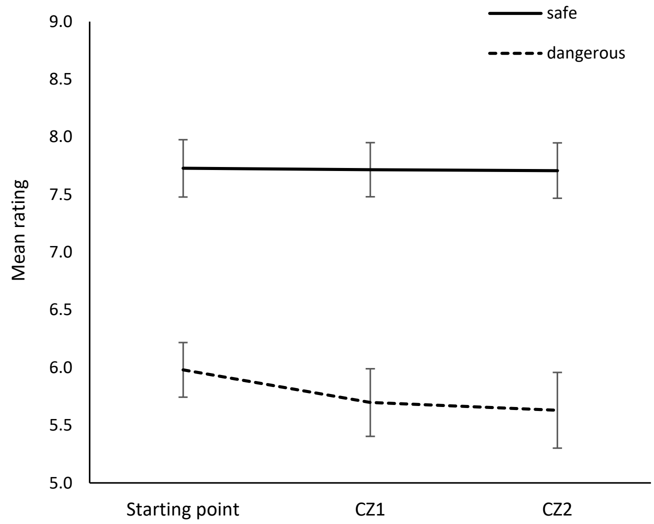

Figure 27: Two-way interaction between location and tool on intention to collaborate (the bars represent the standard errors of the means).

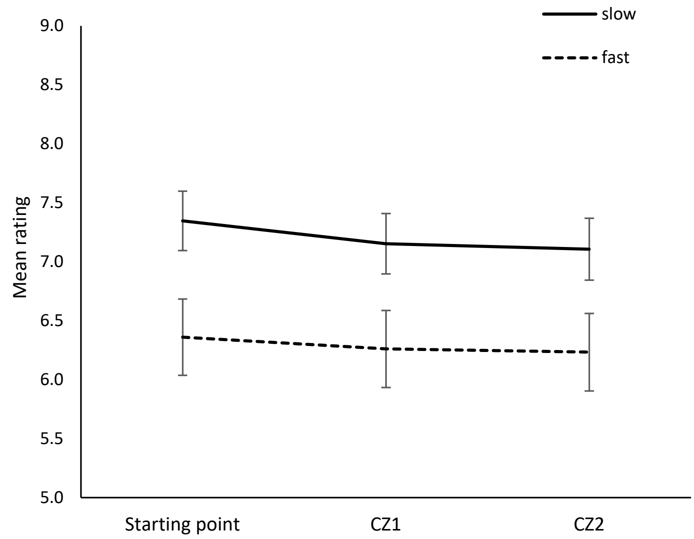

Figure 28: Two-way interaction between location in velocity on intention to collaborate (the bars represent the standard errors of the means).

3.6 Participants age

We also examined possible effects of participants' age in predicting various outcome measures. Participants' age was dichotomized into two age groups, with those aged 22-29 representing emerging adults and those aged 30-57 representing early/middle adults. Age was not a significant main effect for none of the dependent variables. There was a significant, albeit week, three-way interaction between tool, velocity and age on CZ1 There was a great difference in CZ1 between slow and fast movement in the condition of safe tool (as compared to the condition of dangerous tool) in the younger age group, but in the older age group the difference in CZ1 between fast and slow movement was greatest in the condition of dangerous tool as compared to safe tool. A significant three-way interaction between location, velocity and age groups on perceived level of pleasure was found. The difference in pleasure was greater at a starting point compared to CZ1 and CZ2 in the younger age group compared to older age group. However, this interaction effect was small. There was a significant two-way interaction between location and age group, which was again weak. The difference in arousal between younger and older age group was the greatest in the CZ2 condition and the smallest at the starting point. Weak three-way interaction between tool, velocity and age group on arousal was found. The difference in arousal was greater between dangerous and safe tool in the condition of slow movements as compared to fast movement in the younger age group and smaller in the condition of slow movement compared to fast movement in the older age group. In general, age did not prove to be a significant factor when examining various HRI outcome measures.

3.7 Summary of the results

For all measured dependent variables (except deviation) the main effects of tool, velocity, and movement were significant at the 5 % significance level (Table 6). The main effect of location was significant for pleasure and arousal. At the starting point of the approach toward the robot participants experienced higher levels of pleasure and lower levels of arousal. Participants moved closer to the robot, experienced higher levels of pleasure and lower levels of arousal, perceived the robot as safer, and had higher intentions to collaborate with the robot when the robot moved slowly, used a safe tool, and moved up/down, left/right, or performed a circular left/right movement. Participants stopped earlier in front of the robot, experienced lower levels of pleasure and higher levels of arousal, perceived the robot as less safe, and had lower intentions to collaborate with the robot when the robot used a dangerous tool, moved quickly, and performed forward/backwards, random, and circular forward/backwards movements. The effect of the tool was by far the strongest, which could be due to the fact that the robot was using a really dangerous tool – a large kitchen knife – which can normally elicit higher arousal. The effect of velocity was, on average, the second largest effect. The tool of the robot (safe versus dangerous) and velocity of the robot (slow versus fast) were found to be the most important factors of human-robot interaction. The third largest effect was the main effect of movement type, which also should not be neglected when designing a human-robot interaction. Participants felt less safe, experienced higher levels of arousal and unsafety and lower level of pleasure and intention to collaborate when the movements were random and forward/backward. Random movement is probably perceived as more unpredictable and unsmooth. Forward/backward movement can represent a movement that mimics the movement of an attacking or hitting something and therefore provokes unpleasant feelings.

The most frequent significant two-way interactions were between velocity and movement and between location and tool. All two-way interactions were weak, especially compared to main effects. There was just one significant three-way interaction (i.e., between location, tool and velocity on pleasure) and no significant four-way interaction.

Table 6: Summary of significant main effects and interactions.

	Mean deviation	*CZ1*	*CZ2*	*Pleasure*	*Arousal*	*Perceived safety*	*Collaboration*
Location	/	/	/	▯	▯		
Tool type		▯	▯	▯	▯	▯	▯
Velocity		▯	▯	▯	▯	▯	▯
Movement type		▯	▯	▯	▯	▯	▯
LxT	/	/	/	▯	▯	▯	▯
LxV	/	/	/				▯
LxTxV	/	/	/	▯			
TxM				▯	▯		
VxM		▯	▯	▯		▯	▯

Note. L = location, T = tool, V = velocity, M = movement, ▯ = significant main effect or two-way interaction, / = not calculated

3.8 Qualitative data

After the experiment, participants were asked to share observations, feelings and experiences they had during the experiment. Their answers were analyzed using thematic analysis approach. The main themes and corresponding subthemes are shown in Table 7. In general, participants found the experiment interesting and had positive feelings afterwards. This may be (at least partly) explained by sampling bias (individuals that are interested in robotics and similar topics were more likely to respond to our invitation and decided to participate in the experiment). However, it is good to know that robots generally did not evoke negative feelings and states. The participants highlighted all the main effects (tool type, velocity of the robot) and they especially emphasized the importance of the dangerous tool (knife), which had a great impact on their feelings. Some of them also stated that the noise affected their perceptions, i.e., the louder it was, the more uncomfortable they felt. Overall, the participants expressed great confidence in the robot and in the experimental situation. During the experiment, they quickly recognized at which point the robot automatically stopped (if they came to close), and so they recognized the safety zone. They also expressed that they trusted the technology and the robot and that they did not think about a possible error that could occur in the experiment.

Table 7: 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.«
Effect of robot's parameters	*Tool*	»It was unpleasant because of the knife, and just because of it.«	»As expected, when the robot had the sponge, I was more relaxed.«
	Movements	»The most dangerous were those movements that were directed towards me and those that made a very long journey.«	»The unpredictable movements were uncomfortable.«
	Velocity	»The most uncomfortable were the quick movements, the slow ones were not uncomfortable, even when holding the knife.«	»The quick movements were more terrifying.«
	Sound	»Sound has an impact; with louder ones you stop sooner because it's more threatening.«	»I noticed that the sound affected me.«
Trust	*Trust in robot*	»I was not afraid, because I know that the robot does not make its own decisions and that it is controlled.«	»If there were a human instead of a robot, I would have much less trust, instead I trusted the robot.«
	Trust in the experimental situation	»Since we were on faculty, it seemed to me that there would be nothing wrong, because if we were in some other environment, I wouldn't dare to come so close to the robot.«	» I know that the situation was safe.«

4 Conclusion

Our study confirmed the notion that it is important to consider the different robots' parameters when planning human-robot interaction. The tool that the robot holds in its hand is very important. The more dangerous it is, the more uncomfortable and unsafe the people will feel, and they will be less willing to collaborate with the robot. The velocity at which the robot moves is also an important factor. At slower velocities, people will feel safer and more comfortable. Finally, the way a robot moves is also important. People do not feel comfortable with unpredictable movements and movements reminiscent of dangerous actions; they feel most comfortable with movements from left to right and movements up and down, i.e., movements that are perceived as smooth and predictable, and do not present a possible threat (e.g., movement toward the observer). This also affects how close they will approach a robot. Location of the person in relationship to the robot is also an important factor to consider when designing human robot interaction. Standing too close to the robot may evoke negative feelings. After reviewing the participants' observations and experiences after the end of the experiment, we realized that the participants showed a high level of confidence in the safety of the robot; they were sure that the robot would not hurt them because of all safety mechanisms. However, this may be partly due to the experimental situation, so in the future our findings should be verified in a real work environment, where trust in the safety of the robot could be somewhat reduced.

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