Dominance and Movement Cues of Robot Motion

A User Study on Trust and Predictability

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***Abstract*—We investigate the effect of dominant and submissive movement strategies and a movement cue in a human-robot cooperation scenario on perceived predictability and trust. Four different movement strategies in proximal cooperation between a robot manipulator and a human participant were tested in an experiment in which participants had to arrange small objects in a shared workspace working on the same product as the robot. The features of the robot motion were characterized by dominance or a movement cue. The robot modifies its motion in two ways resulting in four different movement strategies: either it stops when the human is in danger of collision (submissive) or not (dominant), and either it performs a backing-off movement cue or not. The participants evaluated the movement strategies in terms of trust and predictability in a questionnaire. We found that the submissive backing-off movement strategy significantly enhanced the users' trust compared to the dominant movement strategy without movement cue. Other strategies showed no significant differences in trust or predictability.**

Keywords—Human Factors; Robotic Systems; Human-Machine Cooperation & Systems

I. Introduction

Humans are increasingly surrounded with moving autonomous systems and robots [1]. When humans and robots share a common space, robot motion should be designed with human needs in mind. Under the term human-robot interaction (HRI) an important distinction between coexistence and cooperation has to be made [2]. In these different paradigms, motion has to be targeted differently, due to the variations in proxemics and the intended or unintended interference of the two partners. In human-robot-coexistence (HRCoex), human and robot share a (work)space during the same time. In human-robot-cooperation (HRCoop), human and robot share a (work)space during the same time and additionally aim towards a common goal or task [2]. For efficient and effective HRCoop, humans should understand the intent and trust the movement of the robot [3]. Movement cues have been shown to affect the perception of robot intent by observers [4] [5], but although there has been research on stylistic effects of robotic motion [6], their effect on human perceived trust and predictability has not been investigated extensively yet.

A. Transferring predictability considerations to human-robot-cooperation

Predictable motion is a basis to match and guide the human's expectations [7]. There are numerous considerations of predictability in HRCoex. Studies have shown that straight line movements of the robot improve human well-being and performance compared to curved movements [8] and are more intuitive and natural for the human [9]. In other studies, projections and auditory feedback were used to enhance predictability of motion [10]. In a similar context LEDs were used to communicate the robot's intent [11]. However, we believe such modalities are less suitable to guarantee predictability in HRCoop considering the close proximity between human and robot and the higher tool-center-point (TCP) speeds that are reached in state of the art cooperative robots. For close cooperation, we believe the human is more likely to pay attention to the "body language" of the robot. Thereby we aim to investigate which robot movement strategy exceeds at communicating intent and awareness in collision avoidance.

B. Trust in human-robot-interaction

As a basis for interaction with the cooperative robot, human trust in the system needs to be established [12]. The concept of trust in automation is built upon reliance and compliance. Reliance describes the extent to which a person relies on the correctness of the autonomous system's behavior. Compliance resembles the extent to which a person agrees to the instructions of an autonomous system [12]. On this foundation, trust in a robot describes the attitude of a person to be willing to be vulnerable to the actions of the robot based on the expectation that it will perform a particular action important to the user, irrespective of the ability to monitor or to intervene [13]. Being able to interpret the robot's intentions thereby plays an important role in the development of trust [1]. This suggests that trust is also closely related to the presence or absence of predictability. The presented study aims to give insight whether dominant or submissive movement strategies or the presence or absence of a movement cue would result in higher users' trust.

C. Dominant and submissive robot movement

Dominance can be defined as the degree to which one actor attempts to regulate the behavior of the other [14]. We call robot motion dominant when the robot continues with its task despite possible collision with the co-working person, forcing the person to avoid it, and submissive when the robot interrupts its movement, allowing the person to complete their planned movement and work on the task. In social interactions, dominance has been shown to correlate with lower trust in the robot [15].

D. Movement cues

Movement cues have the potential to give human co-workers insights into robot intention, which can improve human performance in terms of time to completion (TTC) [16] and improve trust [1]. To achieve this, the motion needs to be predictable. With non-humanoid robots, intent can be expressed by varying the trajectory of motion [17]. Knight et al. [4] showed how non-humanoid robots can use "expressive motion", i.e. motion executed exclusively to communicate robot intent to onlookers. During point-to-point or reaching movements of an arm in a shared workspace, a short backwards movement when the robot gets close to the human is, at the very least, acknowledgement of the other party's presence. We observe such a cue also in human-human interaction, when two persons accidentally reach for the same object at the same time. Users have greater trust in autonomous systems when it is clear that the system is aware of them [1]. What is not clear is if a human-inspired back off movement cue can communicate awareness and thereby enhance trust. In the presented study we designed a back off movement cue to investigate whether movement strategies including the cue would perform better in evaluations of trust and predictability than movement strategies without movement cue both in dominant and submissive motion.

E. Hypotheses

To target the presented problem statement, we formulated the hypotheses *H1* and *H2*.

Trust (H1) and predictability (H2) towards the system differ between four movement strategies.

II. Method

1) Sample: twenty-five healthy volunteers took part in this study (40% female). The average age of the participants was 25.48 years ranging from 18 to 32 years (*SD* = 3.61). No participant reported any motor or sensory disorders. Fifteen participants had no previous experience with robots.

2) Procedure: In this within-subject study, participants stood at position A in Fig. 1 while the movement of the robot was demonstrated without the human in its workspace. They then stood in position B and performed the sandwich assembly task, the robot remaining stationary, in order to give a baseline for participants' execution of the task without HRCoop. Following this baseline condition, the participants performed their task at position B at the same time as the robot performed its task (Fig. 2). The participants' task involved placing four (card cut-out) ingredients, salad (green), tomato (red), cheese (yellow) and ham (pink) on a slice of bread and then covering it with another slice, six times. The sandwiches were placed in order from left to right and top to bottom. All ingredients were on the table as well as a graphical instructions sheet (Fig. 1). The robots task was to pick three bottles of "seasoning" (for logistical reasons, these were empty bottles) and pour their imaginary content on the sandwiches following a preprogrammed path (Fig. 2). Four robot movement strategies were investigated (Tab. 1). During those trials, the different movement strategies were applied in the robot collision avoidance software. A fifth robot movement strategy, which scaled velocity to zero with increasing proximity to the human, was tested in the trials but excluded from this paper as it was irrelevant to our problem statement. After each demonstrated strategy, the participant had to fill out the questionnaire described in section *4)*. The requirements for the fillings in each sandwich were changed for each movement strategy and the robot strategies were introduced in randomized order to avoid distortion from a learning effect. Participants were instructed to perform the task "quickly and precisely". The task was made straightforward enough to be easily explainable, but complex enough that the subjects should be concentrating on their task. The movements of the robot end effector were minimum jerk and linear in Cartesian space on grounds of their ease of predictability for humans [9].

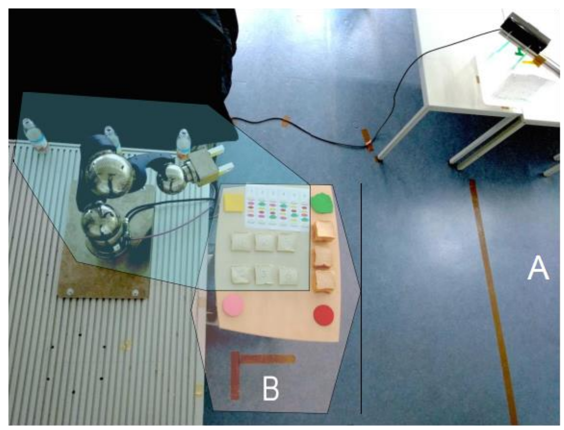


Fig. 1 Experimental area showing the co-working robot, the sandwich ingredients, the bottles and the graphical instruction sheet

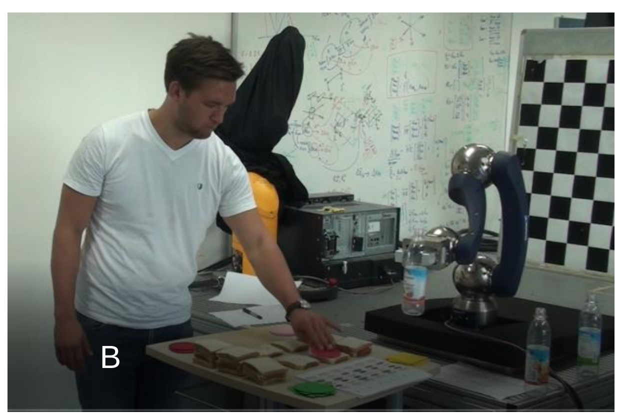


Fig. 2 Participant and the cooperating robot, both performing the task at the same time

3) Robot movement strategies: The four movement strategies we tested are shown in Tab. I; two strategies are *dominant* and two are *submissive*, and in two strategies a *back off* movement is used, whereas in the other two *no cue* is present.

TABLE I Classification of the movement strategies

BD	ND	BS	NS
back off	*no cue*	*back off*	*no cue*
dominant	*dominant*	*submissive*	*submissive*

The control of the robot is shown in Fig. 3. The robot follows a pre-programmed trajectory, and continually checks whether a collision could occur with a nearby human during the time the robot would take to perform a stop. If a collision could occur, the robot state becomes “COLLISION POSSIBLE”. The robot still continually checks if a collision could occur, and as soon as it believes it is safe, the state becomes “COLLISION IMPOSSIBLE” again. In the two *dominant* strategies, even when the robot is in the state “COLLISION POSSIBLE”, it will continue moving at its nominal speed, whereas in submissive trajectories it will come to a stop along the spatial path. During the transition from “COLLISION IMPOSSIBLE” to “COLLISION POSSIBLE”, the *back-off* strategies perform a short (path-consistent) backwards movement for 1 second.

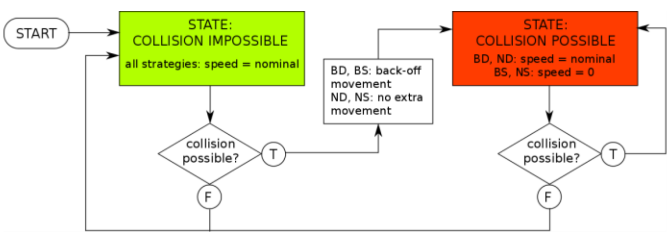


Fig. 3. Robot control

To check whether a collision is possible with the human, the robot 1) calculates a stopping trajectory, 2) predicts the sets of space that the human and robot could reach until the end of the stop, the *Reachable Occupancies*, and 3) checks if they intersect or not.

The stopping trajectory of the robot is achieved by scaling the desired velocity to zero. The duration of the stop t_s and hence the scaling factor δ is based on the vector of current joint velocities $\dot{\boldsymbol{q}}_0$ and maximum permissible accelerations $\boldsymbol{a}$ (set just under the absolute maximum to allow for error):

$$t_s = \max\left(\frac{\dot{\boldsymbol{q}}_0}{\boldsymbol{a}}\right) \qquad \delta = \begin{cases} 1 - \frac{t}{t_s}, & 0 < t < t_s \\ 0, & t \geq t_s \end{cases}$$

Where the division is elementwise, t is the time during the stop and $t = 0$ at the start of the stopping trajectory.

To calculate the reachable occupancies of human and robot, we take the following approach. The robot and the human are each represented as a set of capsules as in Fig. 4, which entirely enclose the parts of each. The forward kinematic function applied to the joint positions (read over CAN bus) gives us the positions of the robot capsules while an Xbox Kinect sensor gives us the positions of the human capsules through the Skeleton-recognition functionality of the Microsoft SDK, at a rate of 30 Hz. The reachable occupancy of the robot is found by obtaining the capsules during the middle of the robot stopping trajectory from the forward kinematics, and extending the radii by half the distance travelled along the trajectory. (This procedure was optimized for speed and not intended to be conservative). Methods exist for quickly and robustly predicting the sets in space that the human can occupy, e.g. [18]. Probabilistic methods such as Gaussian Mixture Models and Hidden Markov Models have also been used for human prediction. Since human prediction is not the focus of the paper, we use a very simple method. The reachable occupancy of the human is based on a maximum upper-body speed of 1.6 m/s from ISO standards [19]. Since there is latency in the sensors and in the control loop, the sensor data is historic. The maximum distance the human can be expected to move during the stopping trajectory is thus $d = 1.6 \cdot (t_s + \Delta t + t_l)$, where Δt is the cycle time (in our case, 2 ms) and t_l is the latency of the sensor (estimated at 33 ms). To predict the human occupancy, we simply extend the radii of the capsules obtained from the sensor data by d.

Finally, pairwise collision-checks are performed between the capsules of the human occupancy and of the robot occupancy; if there is intersection, the decision boxes of Fig. 3 evaluate to true, and if not, they evaluate to false.

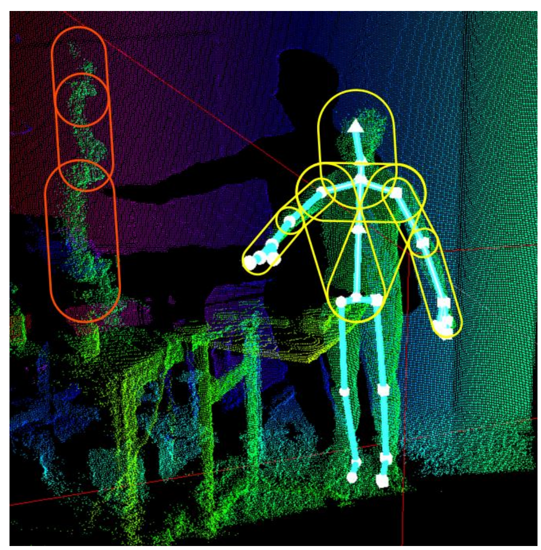
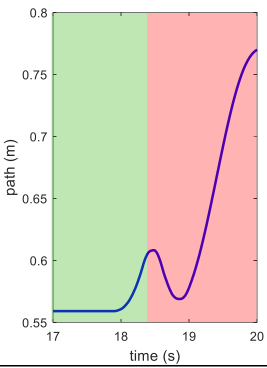
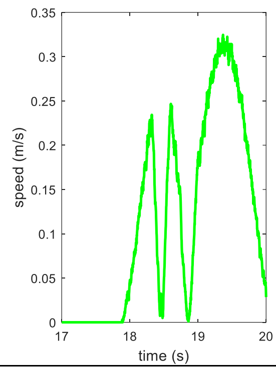
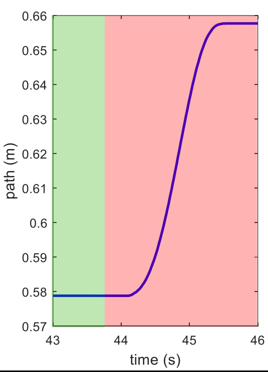
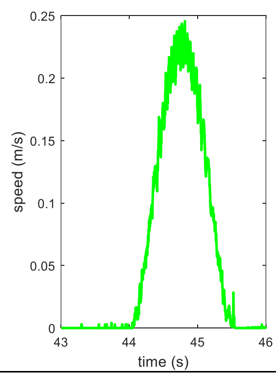
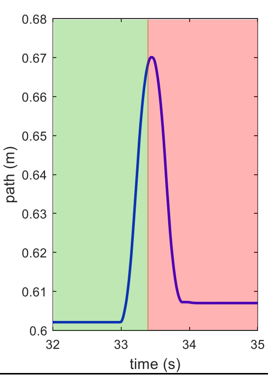
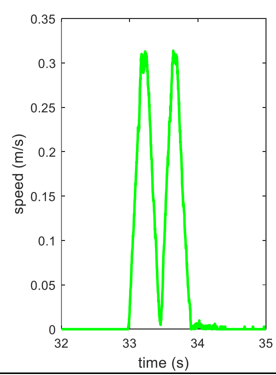
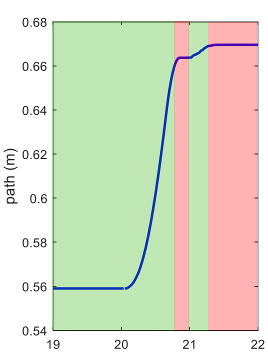
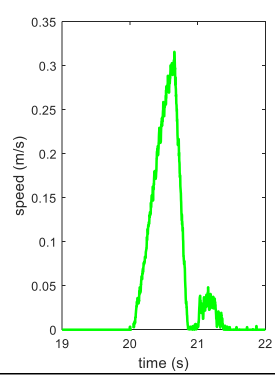


Fig. 4 Robot and human are each represented as a set of capsules for detection of the states “COLLISION POSSIBLE” or “COLLISION IMPOSSIBLE”

TABLE II Exemplified path over time and speed over time diagrams to illustrate two of the strategy-defining parameters - path and speed – as they were perceived by a participant. Green and red shading display whether the robot was in state “COLLISION IMPOSSIBLE” or “COLLISION POSSIBLE”

	Absolute robot TCP path over time example participant 1	Absolute robot TCP speed over time example participant 1
BD - back off dominant		
ND – no cue dominant		
BS - back off submissive		
NS – no cue submissive		

With the exception of ND, none of the movement strategies was exactly the same in terms of position and timing over all the participants, since the human motion to which the robot reacts was unique to each participant (Tab. 2). The examples in Tab. 2 were selected to display typical TCP position and velocity profiles during the operation. The diagrams in the left column display the absolute path travelled by the robot TCP during one straight line movement in reference to the point of origin in Cartesian coordinates. The diagrams in the right column display the speed of the robot’s TCP. The TCP reached maximum speeds of 0.62 m/s. The robot control was implemented in Simulink 2015b and used on a Schunk LWA4P robot arm operating in interpolated position mode, controlled by a Speedgoat Real Time Target Machine through a CAN interface.

4) Measures: A validated questionnaire was used to measure trust and predictability (Cronbach $\alpha = .82$ for reliability on the predictability subscale and $\alpha = .85$ for the trust subscale) [20]. The subscales trust and predictability are comprised of the items displayed in Tab. 3 which are evaluated with a 5-point Likert scale ranging from “strongly disagree” to “strongly agree” and were used for evaluation of the hypotheses *H1* and *H2*. To obtain a measure of trust and predictability, the mean value of the responses to each question within the subscales was calculated. The questions were designed to evaluate the psychological concepts of predictability and trust utilizing a multiple item layout [20], [21], [22]. The α values state that the responses to the questions correlate on a high level and suggest, that the questions in each subscale measure the same attitude. In our case, these attitudes are predictability and trust. The questionnaire is visible on our website (http://www.lfe.mw.tum.de/en/home/).

TABLE III Questions from the questionnaire “trust in automation” [20]

Item	Subscale
The system state was always clear to me	Predictability
I was able to understand why things happened	
The system reacts unpredictably*	
It’s difficult to identify what the system will do next*	
I trust the system	Trust
I can rely on the system	

* invers statement

III. Results and Discussion

In Tab. 4 we present the results of the questionnaire and the mean time to completion (TTC) of the task by the participants and the robot. One participant who gave no answers was excluded from the trust analysis. The scales for predictability and trust are ordinal Likert-scales ranging from 1 to 5. Predictability ratings showed no significant differences. A one-way repeated measures ANOVA was applied to analyze the effect of movement strategy type on mean trust evaluation (Wilks' Lambda = 0.63, F (3, 21) = 4.16, $p = 0.018$, $\eta^2_p = 0.37$). The back off submissive movement strategy BS ($M = 3.31$, $SD = 1.15$) was significantly evaluated better in terms of trust than the no cue dominant strategy ND ($M = 2.63$, $SD = 1.11$) ($p = 0.025$). Evaluations towards other movement strategies differed not significantly.

In the following section we consider the two strategies which showed significant differences in terms of trust. When exposed to movement strategy BS, human TTC ($M = 59.52$ s, $SD = 18.62$ s) was not significantly different compared to movement strategy ND ($M = 60.24$ s, $SD = 13.57$ s). However, the robot had to stop its movement which resulted in much higher robot TTC ($M = 124.8$ s, $SD = 13.27$ s) for movement strategy BS as opposed to strategy ND ($M = 80.2$ s, $SD = 0.82$ s), with an increase of $M = 44.6$ seconds (55,6 %). This means that movement strategy BS is more trustworthy, however, it is worse than movement strategy ND in terms of cooperative efficiency (time until both parties have completed the task).

During both dominant movement strategies, the robot took a lot less time compared to the submissive movement strategies which is due to the fact the robot did not have to stop in dominant strategies, or if so, in the back off dominant strategy BD, only did this once and then continued with its task. However, the human TTC utilizing all four movement strategies and the baseline were not significantly different. This suggests an independence of dominance, and the movement cue on human task performance, which makes submissive robot movement strategies inefficient for cooperation, in this study.

TABLE IV Result table of the mean values for predictability and trust and the time to completion of the task (TTC) of robot and participant

Movement Strategy	Predict-ability		Trust		Participant TTC (s)		Robot TTC (s)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
BD - back off dominant	3.23	1.29	3.01	1.37	60.84	16.24	85.0	2.14
ND – no cue dominant	3.21	1.28	2.63*	1.11	60.24	13.57	80.2	0.82
BS – back off submissive	3.17	1.24	3.31*	1.15	59.52	18.62	124.	13.2
NS – no cue submissive	3.25	1.21	3.31	1.19	57.56	15.39	119.	15.5
baseline	-	-	-	-	53.96	17.04	80.2	-

*significant difference in pairwise comparison $p = 0.025$

A. User feedback

After carrying out the tests, we asked for the users' preferred movement strategy and their reasons why they liked or disliked strategies. We found that reactions to both dominance and movement cue were mixed, with strong opposing opinions. For example, on the subject on dominance:

P 7: *"The robot is obstructing me when it stops"*

P 13: *"It gives me the feeling of a co-working robot, when it stops"*

P 18: *"I found it irritating when the robot stopped or waited for me"*

P 23: *"I found it best when the robot completely ignored me, because then one can estimate what happens next, to some extent"*

P 25: *"It annoyed me when the robot kept on going, this could have lead to collisions"*

On the subject of the "back-off" movement cue:

P 4: *"Backing off was "cool" and I liked that it waited"*

P 5: [found the dominant back-off movement pattern useful because] *"it seemed that the robot took the human into consideration, then continued"*

P 15: *"The behavior of the robot is most natural and humanlike when it backs off"*

Further comments showed that, despite the robot being demonstrated beforehand, some participants took some time to get used to it, whereas others ignored the robot:

P 14: *"At first I was concerned about paying attention to the robot, but later I just ignored it"*

P 22: *"In the beginning, I didn't really pay attention to the robot"*

B. Yielding and taking priority

Previous works claim that humans prefer to perform their own task and make the robot wait, rather than yielding priority to the robot [15], [16]. Observation of human behavior during submissive movement strategies showed that 22 of the participants chose to continue with their task when the robot approached the workspace and then stopped, indicating that they were comfortable assuming a more dominant role in the interaction, whereas only 3 moved their hand or body back to allow the robot to continue, indicating that they allowed the robot to dominate in the interaction.

As shown in the previous section, subjective reaction to dominant movement strategies from the robot is largely a matter of personal preference: dominant behavior elicits different responses. We therefore suggest that the dominance of the robot's movements should be tailored to its human coworker. Various approaches exist to allow the robot to adapt to this. The approach of [24] could help account for this. Here, unknown properties of the human are modeled as uncertain parameters for which the robot has a belief model; the robot updates its belief state by executing actions which probe the human's parameters. In our case, these properties could be the preferences with respect to dominance and movement cues.

C. Longer-term studies

The experiment lasted 20 minutes on average. In an industrial setting, humans are likely to work alongside robots for a much longer time. The fact that there was one trial per movement strategy only, had negative effects on the results. Some comments showed that, despite the robot being demonstrated beforehand, some participants took time to get used to it, whereas others ignored the robot. A higher number of trials utilizing the same movement strategy could have resulted in more substantiated evaluations. As noted in [16], longer-term studies are necessary to determine whether the effects found in this study are weakened or strengthened by longer exposure to the robot and how trust and expectations develop over time. A long-term study will appear as part of follow up work.

IV. Conclusion

We investigated the effect of dominant and submissive movement strategies and a movement cue on perceived trust and predictability in close human-robot-cooperation. Participants found a submissive robot movement strategy with a "back-off" movement cue more trustworthy than a dominant movement strategy without movement cue, confirming hypothesis *H1*. Although previous works have correlated trust to predictability, we did not observe this; also we did not observe significant differences in predictability between robot movement strategies, hence hypothesis *H2* was not confirmed. User feedback to dominance and movement cues are extremely variable and the same movement strategy can elicit very different responses. In this study we tested one movement cue to investigate the effect on evaluations of trust and predictability compared to movement strategies without movement cue both in dominant and submissive motion. In further work, also other movement cues could be designed with the intent to increase trust and predictability. Furthermore, one could vary movement cues in terms of safety distance to the user, robot speeds, accelerations and track participants' gaze, to give quantitative insight into trust and predictability.

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