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Evaluation of Proxemics in Dynamic Interaction with a Mixed Reality Avatar Robot

Jingxin Zhang[1], Omar Janeh[1], Nikolaos Katzakis[1], Dennis Krupke[1] and Frank Steinicke[1]

[1]Human-Computer Interaction, University of Hamburg, Germany

Abstract

We proposed a method that using arm swing of a mixed-reality avatar upon the robot platform to present the moving speed of it. Then a series of studies were designed and performed to investigate the effectiveness of this method and the proxemics when human have dynamic interaction with the mixed-reality avatar robot (Figure 3). Our findings suggest that robot moving speed has a significant effect on the proxemics between human and mixed-reality avatar robot. While attaching an avatar upon the robot did not show a significant influence on the proxemics in dynamic interaction comparing to the baseline situation (robot only). But participants gave positive comments on this method which helped improving perception and prediction on the robot state and its potential applications like marking tiny ground robot. Our work provided references and guidelines for external expression on the robot state with mixed reality for the further research.

CCS Concepts

• ***Human-centered computing*** → *Human-robot interaction; Mixed / augmented reality;*

1. Introduction

When interacting with a robot, human observers wish to comprehend their current state, understand their purpose and predict their further actions [FWL*13, BNS02, GFS07]. Earlier research [LPJY06, FND03, HZH*15] has demonstrated that if we could improve a robot's personality with some extent of social intelligence, the robot will be more predictable and easier to understand. However, this is very challenging to achieve considering the diverse shapes and different locomotion methods of robots. Humanoid robot designs [PKLO05, KPL*05, Bre03, MIM*04] might make robot's behavior easier to perceive and predict by introducing human-like gestures or facial expressions, but constraints on the mechanical build still exist while humanoid designs are not optimal for all kinds of tasks (like traveling in a narrow pipe).

Mixed reality technology provides a solution to this problem. A mixed reality avatar could maintain the original build of robots but present a metaphysical state of the robot by visualization such as gestures, animation or facial expression simultaneously. Furthermore, a mixed reality avatar could help people notice and recognize some tiny ground robots in advance in some complicated or crowded environments, so as to avoid distraction and discomfort when robots suddenly appear nearby or invade their private space. In this paper, we refer to the setup consisting of a robot and a mixed reality avatar as *avatar robot*.

This work specifically focuses on proxemics in dynamic interaction with a mixed reality avatar robot, in which the avatar arm swing animation is chosen to reflect the current locomotion speed of the robot. Perceiving the moving speed of a wheeled robot correctly and then choosing suitable proxemic preferences in a dynamic situation like guidance or head-on encounters could reduce discomfort to nearby pedestrians. The application of mixed reality avatars together with robots raises therefore the question: With a mixed reality avatar presented overlayed on top of the robot, which factors influence the proxemic preferences of humans in a dynamic interaction? We explore the design space by evaluating two elements in a series of user studies which manipulates robot locomotion speed and the avatar visibility.

2. Related Work

2.1. MR and AR in Human Robot Interaction

In a series of papers, Dragone and Holz [DHO06, DHO07, HCO*11] have raised the idea that displaying a humanoid avatar upon the robot platform to broadcast the current state of the robot could help people understand the robot's state more effectively. Those studies, however, include no user evaluation. Similarly, Young et al. proposed a method using cartooning to express different states of the robot [YXS07]. There was no mention in that work on how to apply this approach to express spatial intent. Following up from Dragone et al.'s work, Katzakis et al. explored applying a mixed-reality avatar to signal abrupt direction changes of a robotic platform by using "Body" and "Path" cues [KS18]. Our experiments complement that work, further exploring the augmented surrogate/avatar design space. Other work explored how to apply external visualization and expression to depict the internal state of a robot. For example, Collett et al. explored how to use AR-based visualization to help debugging various sensors of the robot [CM10] Hoenig et al. suggested that mixed reality can reduce the gap between simulation and implementation by enabling the prototyping of algorithms on a combination of physical and virtual objects [HMS*15]. Walker et al. investigated how augmented reality might mediate human-robot interaction by communicating robot motion intent and found that the objective task efficiency could be improved with this method [WHLS18]. Hedayati et al. prototyped several aerial robot teleoperation interfaces using AR and reported improvement in interaction by liberating users from an attention-divided mode [HWS18]. Other research works have also explored how to improve path planning and navigation of robot with the help of augmented reality for higher accuracy and reduced errors [GSSD04,SMC*05,ZHLR14]. Following up from these previous works, we designed our study to investigate if avatar arm swing could indicate and present the moving speed of robot.

2.2. Proxemics in Human Robot Interaction

Young et al. implemented a dog-leash human-robot interface which enables a person to lead a robot simply by holding the leash. The authors evaluated the comfort-distance between the robot and the human [YKR*11]. Walters et al. investigated human-robot and robot-human approach distances and suggested that subjects' personality profiles influenced personal spatial zones in human-robot interaction experiments [WDTB*05]. Furthermore, they ran a study which focused on long-term human-robot proxemics and found that the majority of human-robot proxemic adaptation occurred in the first two interaction sessions, the distance preferences remained relatively steady for the rest of time [WOSD11]. Mead et al.'s work [MM16,MM17] "Autonomous human-robot proxemics" proposed a socially aware navigation method based on interaction potential. Kim et al. investigated how social distance can serve as a lens through which we can understand human-robot relationships [KM14]. Similarly, Mumm et al. explored how people physically and psychologically distance themselves from robot [MM11]. All of these works provided valuable references to the study in this paper.

3. Hypotheses and Setup

In this section, we described hypotheses and setup of the experiment. The goal of the user experiment was to evaluate the ability of participants to match the avatar arm swing animation with the robot movement speed. In addition to this we wanted to explore the proxemics between human and mixed reality avatar robots in dynamic interaction. A schematic layout of the experiment can be seen in Figure 2.

3.1. Hypotheses and Variables

We designed the user experiment in order to test the following hypotheses:

H1: We expected that participants will tend to choose a higher frequency of avatar arm swing when the robot travels faster speed.

We assume this is due to the function of arm swing in human walking which is regarded as a passive movement of gait [MBD13, CAK09]. In order to verify this hypothesis, *robot moving speed* was chosen as a manipulated factor in the first experiment.

H2: When following an avatar robot, with robot moving speed increase, *trust distance* between participants and robot as well as participant's walking variability will also increase.

H3: When participants are on a head-on collision trajectory with an avatar robot, a speed increase by the robot will result in participants having a closer *avoiding distance* from the robot.

We made these two hypotheses considering the extent of trust between a human and robot in a dynamic situation. When following a robot that is moving rapidly participants should theoretically maintain a longer trust distance between themselves and the robot to account for sudden direction or velocity changes of the robot. This is identical to how drivers maintain longer distances from a preceding vehicle when driving at high speeds on a highway. Similarly, when walking towards a faster moving robot, participants will need more time to perceive and understand the next potential movement of the robot so as to reduce the uncertainty, which as a result will cause a shorter avoiding distance between them.

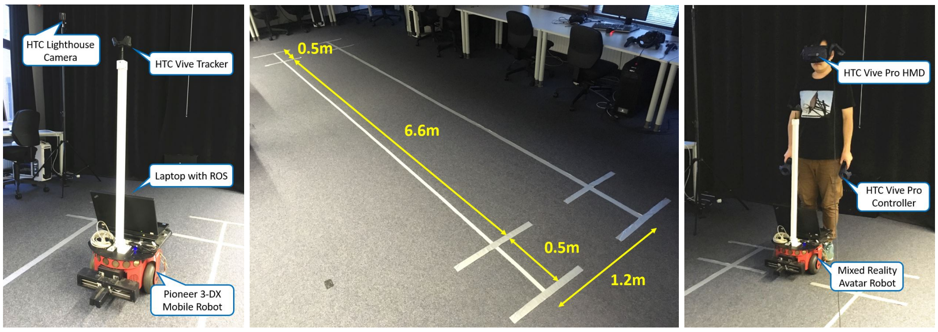
H4: Using avatar arm swing animation to present the moving speed of the robot will have an effect on the trust distance, walking variability and avoiding distance compared to the situation without avatar (robot only).

We assume that using an arm swing animation on the avatar to depict the robot moving speed will help participants to perceive and predict a potential movement of robot better in dynamic interaction. In order to verify the Hypothesis 2-4, *robot moving speed* and *avatar visibility* were chosen as manipulated factors in the second experiment.

3.2. Setup and environment

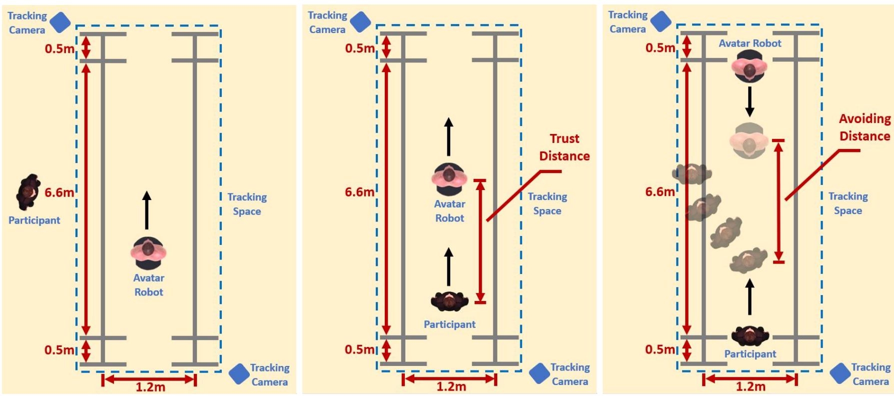
During the experiment all participants were required to wear an HTC Vive Pro HMD with a resolution of 2880×1600 pixels (1440×1600 pixels per eye), which was working in AR mode using the embedded front-facing cameras and the Vive SRWorks SDK toolkit. The diagonal field of view is approximately 110° and the refresh rate is 90Hz. An HTC Vive tracker was fixed on top of a pole for enhanced tracking (Figure 1). The mixed reality avatar had a height of 1.75m and the setup guarantees that the avatar would stay superimposed on the robot consistently throughout the experiment. We used Unity3D for rendering the mixed-reality avatar and communicating with the robot. A laptop running Robot Operating System (ROS) was connected with the robot to receive the commands from Unity and control the robot's movement. During the experiments, the lab environment was slightly dimmed and quiet. Participants used HTC Vive controllers as input devices to perform the specific tasks described below.

The avatar attached to the robot had a neutral facial expression (Figure 4). Two reasons motivated us to only show the avatar torso in the studies: First, avatar legs in mixed reality would have to be overlayed on the physical robot, which might have occluded the



(a) (b) (c)

Figure 1: Hardware setup, environment and participant: (a) Mixed-reality avatar robot consisting of an HTC Vive tracker, a laptop running Robot Operating System (ROS) and a Pioneer 3-DX mobile robot. (b) The experimental environment. (c) Ready state of participant and robot in the task "walking following an avatar robot".



(a) (b) (c)

Figure 2: Schematic layouts of experiments: (a) Avatar arm swing estimation: participants wearing HMD stood outside of tracking area, perceived and adjusted the most natural frequency of avatar arm swing with controllers during robot travelling in different speed. (b) Walking following an avatar robot: distance between participant and avatar robot was defined as "*trust distance*". (c) Walking towards an avatar robot: distance between participant and avatar robot when participant changed his walking direction to avoid a potential collision was defined as "*avoiding distance*".

physical robot, confused participants and thus result in safety issues. Second, in actual scenarios like navigating through a crowd in a busy city, legs are often occluded by torsos of other bystanders. Furthermore, as a passive motion of gait, arm swing frequency provides information on step frequency as well. For these reasons, only the avatar torso was used.

4. Experiment

4.1. Arm swing frequency estimation

The first experiment attempts to determine what is the most natural match between the avatar's arm swing frequency and the robot moving speed. In this part, participants were asked decide the arm swing frequency of a mixed reality avatar based on the locomotion speed of a mobile robot from perspective of a bystander. The schematic layout of this study could be seen in Figure 2a. During the experiment, participant mounted an HMD and held the controllers in their hands. They were required to stand outside the tracking space (Figure 3a). The distance from the standing point to the robot's moving trajectory was set as 1.5m in the social space based on Hall's proxemic zones [HBB*68]. When the study began, participants clicked the trigger button on the controllers to awake the avatar robot to move forward in a specific speed. Three speeds (0.8m/s, 1.0m/s and 1.2m/s) were chosen for the robot to match a person's walking based on previous research [HMRC99]. During the trial, participants were allowed to follow the robot movement by rotating their head freely. The avatar was displayed 1 second after the robot's departure to avoid incongruities during the robot's acceleration to the respective speed. The default frequency of avatar arm swing was set as 1Hz (1 cycle for each arm per second). Furthermore, we applied gains to enable participants to change avatar arm swing frequency. With this method, the real frequency of avatar arm swing could be decided as $f_r = g \cdot f_d$, where f_r was the real frequency of avatar arm swing, f_d was the default frequency set as 1Hz and g was the applied gain. The default gain when robot's departure was 1.0. With the robot moving, participants needed to observe the robot speed and adjust the avatar arm swing frequency to match it. Participants could accomplish this by pressing the left or the right button on the touchpad of the controllers. The gain could be modulated in a range of 0.6 to 1.4 in steps of ± 0.1 per click, and affect the avatar arm swing frequency in real time. In order to guarantee that for each speed participants had a fixed duration to observe and decide on the arm swing frequency, the avatar display time was set to 6 seconds for each trial. The gain applied to the avatar arm frequency at the end of the 6 second run was kept as the participant's chosen gain for that trial. Each level in the speed factor was tested 4 times for each participant.

15 participants were invited from <anonymized> to take part in the first experiment (ages 21-40, mean age 26.87, SD = 6.323). All participants had normal or corrected to normal vision and most of them (13/15) had prior experience with a mixed reality headset. In summary, the experiment was a within subjects design with 3 robot speeds $\times$ 4 repetitions for a total of 12 trials. 15 participants $\times$ 12 trials per participant $=$ 180 total trials collected. All of the trials appeared in randomized order. The experiment lasted for around 15 minutes.

4.2. Proxemics with avatar robot

With the results from the first experiment, we used the avatar arm swing to present the corresponding robot moving speeds and performed this proxemics experiment, in which we focused on the proxemics between a human and a mixed reality avatar robot in dynamic interaction. The experiment included two tasks: walking following and walking towards an avatar robot. We mixed the task order based on the participants' ID: participants with odd ID started with *"following task"*, while the other participants conducted *"towards task"* firstly.

In the following task, we investigated the distance between a moving avatar robot and a following person in a simulated guidance scenario, which was defined as *"trust distance"* in Figure 2b. 3 robot moving speeds (0.8m/s, 1.0m/s and 1.2m/s) which has been tested in the first experiment and 2 avatar visibility (visible and invisible) was selected as factors in this task. Before the experiment, participants mounted HMD and holding controllers stood on one end of tracking space, a mixed-reality avatar robot was placed in front of the participants without space remained (Figure 1c). When the study began, participants clicked the trigger button on the controllers to awake the avatar robot to move forward in a specific speed. For visible situation, the avatar was displayed 1 second after the robot's departure to avoid incongruities during the robot's acceleration to the respective speed. The avatar arm swing frequency was set based on the results of the first experiment to present the state of robot. Participants were required to perceive the increasing distance between avatar robot and themselves. When the distance satisfied their requirements, they started to walk following the avatar robot (Figure 3b). Again, in order to guarantee that for each speed participants had a fixed duration to observe and decide the trust distance, the avatar display time was set to 6 seconds for each trial. After that, the avatar robot stopped automatically. For invisible situation, participants perceived and followed an robot only and adjusted the trust distance between each other in the process. For each trial, we recorded the trust distance in every frame with a frame rate of 75fps from participants' departure to the stop of avatar robot.

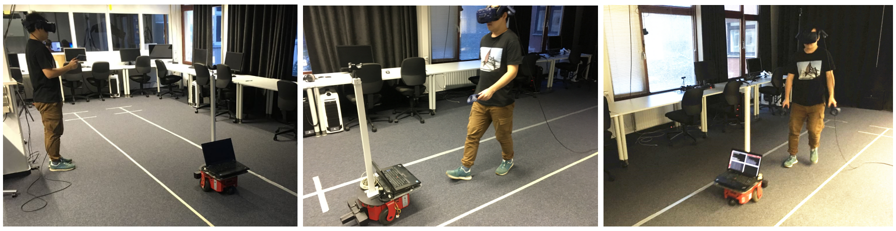
In the towards task, we investigated the distance where participants changed their directions to avoid a potential collision from a head-on approaching robot in a simulated encountering scenario, which was defined as *"avoiding distance"* in Figure 2c. Similarly, we chose the same factors as the following task: 3 robot moving speeds (0.8m/s, 1.0m/s and 1.2m/s) and 2 avatar visibility (visible and invisible). Before the experiment, participants mounted HMD and holding controllers stood on one end of tracking space, while a mixed-reality avatar robot was located on the opposite end. When the study began, participants clicked the trigger button on the controllers to awake the avatar robot to move forward in a specific speed. At the same time, participants started walking towards the avatar robot (Figure 3c). Again, for visible situation, the avatar was displayed 1 second after the robot's departure and stayed for 6 seconds with corresponding arm swing frequency based on the moving speed. During the process, participants were required to perceive and evaluate the distance between the approaching avatar robot and themselves, and changed their directions in a suitable distance to avoid a potential collision. For invisible situation, participants walked towards an robot only and decided the avoiding distance between each other in the process. For each trial, we recorded positions of participants (HMD) and avatar robot (Vive tracker) in every frame with a frame rate of 75fps from the robot's departure to its stop.

14 participants were invited from <anonymized> to take part in the second experiment (ages 20-37, mean age 26.36, SD = 4.765). All participants had normal or corrected to normal vision and most of them (10/14) had prior experience with a mixed reality headset before. In summary, the experiment was a within subjects design with 3 robot moving speeds $\times$ 2 avatar visibility $\times$ 2 repetitions for a total of 12 trials for each task. 14 participants $\times$ 12 trials $\times$ 2 tasks per participant $=$ 336 total trials collected. For each task, all of the trials appeared in randomized order. The experiment lasted for around 40 minutes.

Before the experiment, participants were allowed to have some training trials to check if they understood the procedure. After each trial, the robot was manually positioned for the next trial. When the participant and the robot were ready, the operator would give a permission to the participants, then participants could click the trigger button again to begin the next trial. During the experiments, participants were allowed to have a break at any time.

5. Results

We performed a normality assumption check for all factor levels using the Shapiro-Wilk test [Roy82] before the analysis, and in a few cases the results did not show a strong indication of normal distribution. However, as shown in previous research [GPS72, HRHO92, LKK96], moderate deviations from normality can be tolerated by ANOVA.



(a) (b) (c)

Figure 3: Experiment views from a third-person perspective: (a) Avatar arm swing frequency estimation. (b) Walking following an avatar robot. (c) Walking towards an avatar robot.

(a) (b) (c)

Figure 4: View of participants during the experiment (images captured through HTC Vive Pro HMD): (a) Avatar arm swing frequency estimation. (b) Walking following an avatar robot. (c) Walking towards an avatar robot.

For arm swing frequency estimation experiment, a plot for robot moving speed on preferred avatar arm swing frequency could be seen in Figure 5a. As the only factor tested in this experiment, *robot moving speed* had a significant effect on *preferred avatar arm swing frequency* ($F_{2,28} = 12.58, p < 0.01, \eta^2 = 0.280$). For the following task in proxemics experiment, a plot for robot moving speed and avatar visibility on trust distance could be found in Figure 5b. ANOVA results showed that *robot moving speed* had a significant effect on *trust distance* ($F_{2,26} = 44.41, p < 0.01, \eta^2 = 0.568$). However, there was no significant effect from *avatar visibility* on *trust distance*. There was also no significant interaction effect (robot moving speed:avatar visibility) on *trust distance*. In addition, a plot for robot moving speed and avatar visibility on walking variability could be found in Figure 5c. ANOVA results suggested that *robot moving speed* had a significant effect on *walking variability* ($F_{2,26} = 33.84, p < 0.01, \eta^2 = 0.542$). No significant effect from *avatar visibility* and no significant interaction effect (robot moving speed:avatar visibility) on *walking variability* was verified. For the towards task, a plot for robot moving speed and avatar visibility on avoiding distance could be found in Figure 5d. ANOVA results represented that *robot moving speed* had a significant effect on *avoiding distance* ($F_{2,26} = 5.084, p < 0.05, \eta^2 = 0.137$). No significant effect from *avatar visibility* and no significant interaction effect (robot moving speed:avatar visibility) on *avoiding distance* was found. Furthermore, for the significant factor *robot moving speed*, we conducted pairwise t tests to check if there was significant difference between each level of the factor. The results of pairwise t tests on *robot moving speed* was presented in Table 1.

In a post-experiment questionnaire, participants were invited to comment on their experience with the avatar robot. Positive comments were mainly on the improvement of the perceptive process and potential use, e.g.: "I trusted the avatar and thus I did not have to look at the floor in order to guess where the robot is. The avatar helped me to avoid collisions and the interaction was more natural to me"; "I like how robots could be represented in future. Very useful for small robots near the ground". 2 participants gave negative feedback by complaining about the resolution of HMD and slight motion sickness because of occasional tracking time delay.

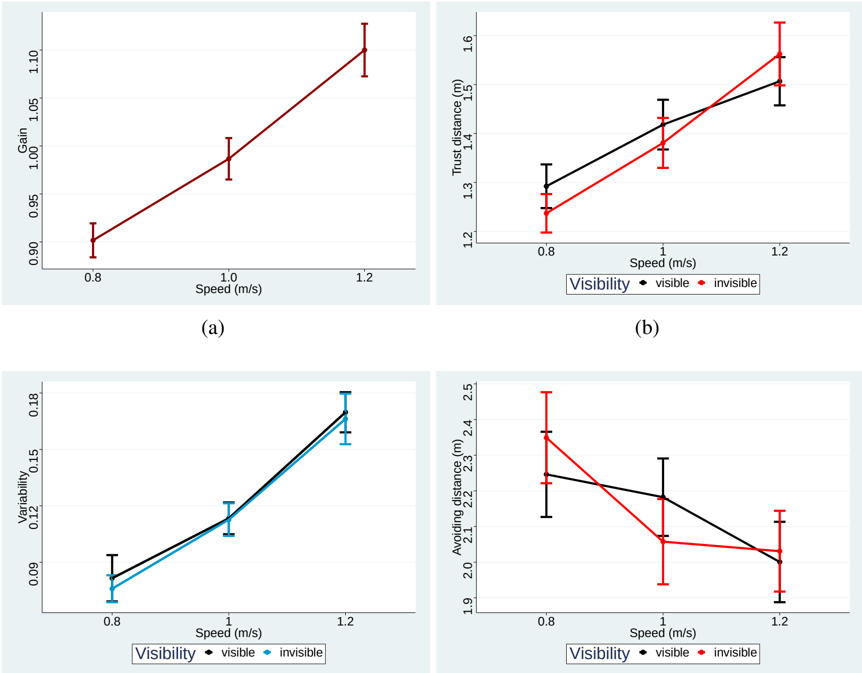
Table 1: Results of pairwise t tests on *robot moving speed*.

Arm Swing Frequency			*Trust Distance*		
	0.8	1.0		0.8	1.0
1.0	0.0031	-	1.0	0.009	-
1.2	6.5e-08	0.0031	1.2	1.3e-06	0.014
Walking Variability			*Avoiding Distance*		
	0.8	1.0		0.8	1.0
1.0	0.00034	-	1.0	0.272	-
1.2	3.3e-12	1.5e-06	1.2	0.054	0.358

6. Discussion

6.1. Preferred Arm Swing Frequency

The results confirm our hypotheses to some extent. Figure 5a suggested that the preferred avatar arm swing frequency showed a linear correlation with robot speed. In addition, standard deviation also increased slightly with the robot moving speed growing. Results suggest that people tend to match a faster moving robot with



(a) (b) (c) (d)

Figure 5: Results of experiment: (a) Effect of robot moving speeds on preferred avatar arm swing frequency. (b) Trust distances with different robot moving speeds and avatar visibility. (c) Walking variability with different robot moving speeds and avatar visibility. (d) Avoiding distances with different robot moving speeds and avatar visibility. The error bars in figures indicate the standard error (SE).

faster avatar arm swing frequency. A possible explanation for this is that as a passive motion of walking gait, arm swing frequency could be also regarded equal to the frequency of legs. When walking in a faster speed, most people preferred to choose keeping their step length but increasing their step frequency as the solution, which conversely caused the results in the arm swing frequency estimation study. Considering the significant effect and the relevant results above, avatar arm swing frequency is an effective method to illustrate the current speed of a robot.

6.2. Trust Distance and Walking Variability

Analysis of the robot moving speed and avatar visibility on trust distance (Figure 5b) suggests that robot speed had a significant effect on the trust distance, however, avatar visibility and interaction effect had no significant influence on the trust distance. Overall, for both avatar visibility (visible and invisible), the trust distance exhibited a increasing trend as the robot speed increased, which suggests when following a faster moving avatar robot, participants tended to choose a larger trust distance. This result has verified our second hypothesis. A potential explanation on the result was due to increasing difficulty in perceiving and predicting the subsequent movements or sudden direction changes of the robot. When it became more difficult and complicated to get accurate perception and prediction on a uncertain situation, people were used to keep more space for safety, which led to a longer trust distance between human and robot in our case.

Furthermore, it was worth noticing that the growth of trust distance for the visible avatar had an obvious deceleration within a robot speed range of 1.0m/s - 1.2m/s, while the trust distance for the invisible avatar showed a nearly linear correlation throughout the whole interval of robot speed we chose. This result suggests that within some specific range of robot moving speed, the arm swing animation could help participants to perceive and predict a further motion of robot better and as a result influenced the trust distance to some extent. In addition to this, the standard deviation of trust distance when walking following a robot only in invisible situation became larger with increased robot speed, while when walking following a robot with a visible avatar, the standard deviation of trust distance did not show an obvious change. This result suggests that participants could better adapt to the change in speed when following a robot with a visible avatar. More rigorous study is needed before we can make strong conclusions.

To evaluate the walking stability of participants, we looked at participant's walking variability within each trial. Variability exhibited a rising trend with the robot moving speed increase (Figure 5c). This result suggests that participants had a more stable walking gait when walking following an avatar robot with a lower moving speed. In addition to this, avatar visibility showed a very similar changing trend except for some slight difference in the speed of 0.8m/s and 1.2m/s. We will discuss more about the effect of avatar visibility in Section 6.4 below.

6.3. Avoiding Distance

In general, avoiding distance exhibited a decreasing trend with the robot moving speed increasing in Figure 5d. One explanation of this phenomenon was that, when walking towards an approaching avatar robot with a faster moving speed, it is more challenging for participants to perceive and predict the subsequent motion of the robot than when the avatar robot in moving with a slower speed. In this case, participants usually needed a longer perceiving and reacting time to predict robot's potential trajectory, such that they could improve the prediction accuracy and make an effective avoiding behavior. Therefore, avoiding distance showed a decreasing trend with the robot moving speed increasing generally.

In addition, in different speed ranges, the effect of avatar visibility on avoiding distance was slightly different. For visible avatar, avoiding distance decreased slowly within the range of 0.8m/s - 1.0m/s but dropped fast within range of 1.0m/s - 1.2m/s. While for invisible avatar, avoiding distance showed a rapid decrease within 0.8m/s - 1.0m/s but a slow decrease within 1.0m/s - 1.2m/s. One possible reason for this was due to the difference of participants' perceiving ability to the robot moving speed when facing a towards-moving robot with or without an avatar. This conversely suggests that attaching an avatar to the robot to present the current state changes an observer's perceptive ability. However, this analysis would require further verification in future research.

6.4. Avatar Visibility

For all the measurements (trust distance, walking variability and avoiding distance) we tested above, avatar visibility did not show a significant effect. The reason of this result we thought was due to the spatial layout of robot and mixed-reality avatar. In other word, when walking following or towards an avatar robot, what participants focused on and perceived was not only the robot or the avatar, but a cylinder space that consisted of robot and avatar together (Figure 6). The proxemics between participants and avatar robot should be decided by this cylinder space which could be also regarded as the real working range or an effective factor that would influence the proxemics significantly during a dynamic interaction between human and avatar robot. According to our analysis and conjecture, in our finished study, the mixed-reality was attached on top of the robot and the size of them were almost the same, which did not have a significant change on the cylinder space we mentioned above comparing with the situation of robot with invisible avatar even though there was slight improvement on perception. Therefore, there was no significant effect of avatar visibility on trust distance, walking variability and avoiding distance found in our study.

6.5. Limitations

Normally, people's arm swing amplitude when walking in different speeds should be slightly different. In our first study, however, arm swing amplitude was fixed to the same level. Arm swing frequency was the only manipulated factor. However, given the limited speed range in our study, the influence of this limitation can be ignored. Another limitation comes from the limited effective tracking range of the tracking system. This tracking limitation was the reason why we did not build a longer tracking space for participants to walk inside. A walking space beyond effective tracking range would cause problems like tracking offset or unstable avatar attachment. We solved the limitation of limited testing distance by giving participants enough training trials before the experiment, such that they could get familiar with the avatar robot well in advance and reach a stable level soon after the experiment was started.

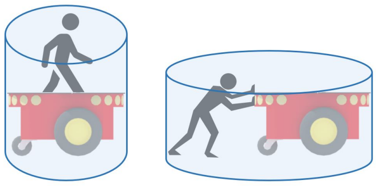


Figure 6: Two cylinder spaces due to different spatial layouts of robot and mixed-reality avatar.

7. Conclusion - Future Work

We presented a method for using arm swing frequency of a mixed-reality avatar attached with robot to effectively communicate the moving speed. Using this arm swing method, a series of studies were performed to test and evaluate proxemic preferences including trust and avoiding distance between a human and mixed-reality avatar robot in dynamic interaction. Our findings suggest that robot moving speed has a significant effect on the proxemics between a human and mixed-reality avatar robot while avatar visibility did not show a significant influence on the trust and avoiding distance. We have analyzed the data and offered potential answers which would be valuable for the future of mixed reality robotics. In our studies, visual information was designed as the only way to perceive robot motion without taking any other cognitive channels like audio and haptic assistance into consideration, thus the results in this paper could be regarded as a conservative reference for some application scenarios such like using robot for guidance in hospital or for ground cleaning in train station or building corridor.

There are still interesting questions that remain for future work, for example: how could people evaluate and decide proxemics in a more complicated scenario like multiple moving avatar robots? How will the avatar's body posture, facial expression or audio influence the interactive process? What will be the results if we separate the avatar away from the robot and establish different spatial layouts of robot and avatar? These remain as open research topics for future research.

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