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Comfortable crossing strategies in human-robot interactions

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 Comfortable crossing strategies in human-robot interactions

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Abstract

To minimize human discomfort and negative attitude towards a robot, it is important that robots navigate in a socially aware manner. One navigation scenario is the human-robot crossing scenarios, where a human and robot are on a path to cross each other. As unpleasant encounters can cause discomfort, the aim of this study is to investigate what a comfortable human-robot crossing scenario looks like. In this study, participants took part in a human-robot crossing scenario where the robot followed four different paths at three different speeds. Results showed that people either pass in front or behind the robot, and that this is dependent on robot path, but not robot speed. Four clearly identifiable human paths were found. Additionally, humans felt more comfortable when an increased minimum distance between them and the robot was kept. More in-depth analysis shows that this effect only holds when the robot is on trajectory to arch behind the human. The distance between robots and humans is dependent on the angle between them. Furthermore, people indicated to experience a less comfortable crossing when the robot moved at the highest speed of 0.85 m/s. No differences were found between the two lower speeds of 0.55 m/s and 0.70 m/s. Finally, comfort was found to be higher at a shorter difference in path length between the human and robot. This was again only true when the robot is on trajectory to arch behind the human. These results show what a comfortable human-robot crossing scenario looks like, it provides a step towards designing more comfortable human-robot crossing scenarios, and it helps guide future research.

Introduction

Nowadays, there are many places where humans and robot share spaces. In some situations, people and robots have difficulty working together. Unpleasant situations can occur and cause discomfort and a negative attitude, for example when the robot acts in an unpredictable manner (Triebel et al., 2015). Additionally, previous human-robot research has already shown that children may engage in non-social or even aggressive behaviour towards robots. Examples of these behaviours are avoiding the use of the robot, putting the robot in situations it cannot get itself out of, breaking the robot by removing parts of the robot, or by damaging the robot with aggressive behaviour (Yamada, Kanda, & Tomita, 2020). Similar behaviour is shown for adults in early implementation of public service robots in public spaces (Salvini et al., 2010).

In some of those places, both the human and robot must be able to move around each other in the same space. Examples include apple orchards where the robots drive around apple trees to pick apples, while humans perform their own separate tasks at the orchard (Vasconez, Kantor & Fernando, 2019) or robots navigating airports to guide passengers to their destination (Triebel et al., 2015).

A scenario that can occur when humans and robots share a space and move around is in human-robot crossing scenario, where a human and robot are on a path to cross each other. An example of this interaction can be found in hospital transport robots (Zheng, Wu & Chen, 2021). Knowledge of human-robot interactions is lacking in the context of crossing interactions. By investigating how humans experience interactions with a robot, social conventions for robots can be formed and used as a basis for designing robot behaviour. This may allow for a more pleasant experience for humans who share environments with moving robots (Rios-Martinez, Spalanzani & Laugier, 2015).

Crossing scenario

A crossing scenario is a scenario where both a human and a robot are on walking trajectories towards a goal. Their paths to get to the goal are perpendicular to each other and the human and robot will arrive at the point of intersection at approximately the same time. In this scenario the human, the robot, or both need to change speed or trajectory to avoid collision.
The task of the robot in this crossing scenario can be categorised as an obstacle encounter task. Common tasks metrics for obstacle encounter tasks include effectiveness measured through time to goal, and deviation from path. General metrics of robot tasks include subjective ratings such as comfort and effort (Steinfeld et al., 2006).

**Personal space & path planning**

Many different algorithms exist that focus on robot obstacle avoidance and path planning for robots. Out of all research on robot path planning, most papers focused on simulation analysis instead of real-world applications (Patle et al., 2019). However, studies on human-robot interactions are often lacking a well-grounded theoretical basis from human-human interactions (Leichtmann & Nitsch, 2020).

In human path planning, people only adopt trajectories when the risk of a collision exists. In crossing scenarios between two humans, one person typically speeds up slightly and moves in front while the other person slows down slightly and moves behind the other person (Olivier et al., 2012). In human-robot crossing scenarios people adopt a similar strategy as they do in human-human scenarios, although humans give way to the robot 8% more often than they would in human-human scenarios (Vassallo et al., 2018).

Personal space in human proxemics is divided in four zones: the intimate zone (within 0.45 m), the personal zone (between 0.45 m and 1.2 m), the social zone (between 1.20 m and 3.5 m), and the public zone (outside 3.5 m). Those zones are ideally reserved for their own social interactions. The personal zones are for stationary situations and have a circular symmetry (Hall, 1966). However, in scenarios where people are moving around the personal zone takes on an oval shape, having a larger area in the front than to the sides of a person (Gérin-Lajoie, Richards & McFadyen, 2005). While studies on personal space in human-robot proxemics exist, they have varying results (Rios-Martinez et al., 2015) and comfort is not quantified (Neggers et al., 2018).

**Comfort, speed, effort, and efficiency**

Several metrics are important in human-robot interactions, this section will explain the most important metrics.

To minimize human discomfort and negative attitude towards a robot, it is important that the robot navigates in a socially aware manner (Rios-Martinez et al., 2015). In human-robot science it is common practice to use human-human conventions as a starting point on how a robot is perceived and how a robot should behave.

When two people are walking, the minimal distance they will keep from each other can be predicted based on their current paths and speeds. This minimal distance is the minimum distance between the two persons if both continue their current paths at a continuous speed. People can intuitively predict this minimum distance while taking part in an ongoing crossing scenario and will either take no special action and follow a straight path at constant speed or take (shared) actions to increase this predicted minimum distance (Olivier et al., 2012).

Increased comfort with increased minimum distance is also observed in human-robot passing scenarios, where a human and robot walk past each other (Neggers et al., 2018). However, it is not currently known whether the effect found in human-robot passing scenarios holds true for human-robot crossing situations. During human-robot crossing scenarios, speed, effort, and efficiency are also relevant variables that should be considered when studying these interactions.

In human-robot interactions where a robot moves in the vicinity of a human, comfort increases when robot movement speed is lowered at close proximity (Lasota, Rossano & Shah, 2014). However, it is
unknown whether this is also true during human-robot crossing scenarios. Additionally, robot speed is an important factor when considering safety around robots (Vasconez, Kantor & Cheein, 2019).

Effort is a common subjective and non-subjective metric in human-robot interactions. Effort can be measured in a non-subjective manner based on the time that is required to complete a certain task, or in a subjective manner through survey or interview methods (Steinfeld et al., 2006). Additionally, it was found that the person that crosses last in robot-crossing scenarios (i.e. went behind the first crosser) takes a larger share of the total effort upon themselves (Silva et al., 2018).

Research Question
To be able to prevent unpleasant situations and discomfort, and to improve human-robot cooperation, the following research question will be answered: What does a comfortable human-robot crossing scenario look like?

As people feel more comfortable with a larger distance between themselves and the robot during human-robot passing situations (Neggers et al, 2018), it is expected that (H1) comfort is higher with increased minimum distance between human and robot during crossing scenarios.

Since comfort is generally higher when a robot moves at lower speeds around a human in human-robot scenarios (Lasota et al, 2014), this is expected to hold true in a human-robot crossing scenario: (H2) comfort is higher when the robot moves at lower speeds around the participant.

People prefer to share effort in human-human interactions, and effort can be measured in walked path length during human-robot interactions (Silva et al., 2018). Therefore, it is expected that (H3) humans will feel more comfortable when the path length of the human is shorter than or equal to the path length of the robot.
Method

Participants & design
Participants for this experiment were recruited by sending invitations through the ARCHIE participant database of the TU/e and using convenience sampling. Participants had to be able to speak English and comfortably walk for at least one hour. Due to COVID-19 restrictions, the maximum age was set at 65.

Twenty-four participants aged between 20 and 59 years old ($M = 28.0$, $SD = 11.4$) participated in this experiment, of which 13 were female and 11 were male. The experiment had a $3$ (robot speed of $0.55$ m/s, $0.70$ m/s, and $0.85$ m/s) x $4$ (robot did not deviate, robot stopped, robot arches left, robot arches right) within-subjects design. Each series of 12 trials was done three times in random order, for a total of thirty-six trials per participant.

Participants were asked about their experience with robots. Nine participants answered that they had no experience, nine participants answered that they had experience from taking part in studies with robots, six participants indicated to have some experience with controlling robots from a course on robotics within a single university course.

Materials & experimental setup
The setup of the experiment is shown in Figure 1.

![Figure 1](image)

*Figure 1. Each trial consists of two parts. To start the trial the participant will walk the path as shown in Part A. After walking the path and arriving at the start of part B, the human continues straight ahead to a laptop, with the possibility of deviating from the path. Path B1 follows a straight line. Path B2 follows a straight line, but with the robot stopping in between. Path B3 has a half-circle deviation to the left. Path B4 has a half-circle deviation to the right.*

Each trial can be separated into two parts. During Part A, the participant follows a predetermined path, and the walking speed of the participant is determined. Part B contains crossing paths with a robot. During this part, the human no longer follows a predetermined path. Instead, the human is instructed to move towards a goal location following any path or speed they find comfortable. In the meantime, the robot is moving at one of three speeds ($0.55$ m/s, $0.7$ m/s, $0.85$ m/s) and follows one
of four paths. The exact start time that the robot starts moving is dependent on the speed of the participant during Part A and is set such that if the participant would follow a direct path and keep the constant speed of Part A, the robot and human would arrive at the crossing point at exactly the same time.

The experiment was conducted in the TU/e VR lab. This lab has dimensions of approximately 5.5 x 8 meters. On a desk a computer was placed, that was used by the experiment leader to control the robot and to retrieve data from the tracking system (PhaseSpace Motion Capture). Twelve cameras attached to this system tracked the location of a set of two trackers attached to the participant using a hat and a set of six trackers attached to a robot.

The robot that was used is the FAST robot, as shown in Figure 2. This is a machine-like looking robot of approximately 1 meter high and a base of approximately 75 cm x 65 cm. The robot has a screen, but this was not utilized during this experiment. The FAST robot has a maximum acceleration and deceleration of approximately 0.7 m/s². The maximum speed is 1.7 m/s, but this speed could not be reached in the limited space of the experiment room. The FAST robot was connected to the previously mentioned computer in the lab.

![Figure 2. Picture of FAST robot.](image)

**Robot control**

The methods to control the robot were newly developed for this study. Prior to the start of this project, the tracking systems and the robot had different control PCs and could not communicate with each other. An overview of the networking setup before the start of this study is shown in Figure 3.
Both the control PC and tracker system are connected through the university network, which is protected. Communication to the tracker system is only allowed from the Tracker Control PC, no other devices can access and control the tracker system. Both the robot and the robot control laptop are connected to a networking switch over WIFI. Access between two devices within the university network is heavily restricted.

To solve that the different control PCs could not communicate, the networking was adjusted in such a way that a single control PC could communicate with and control both the tracker system and robot. The tracker control PC is now connected to the university network with a network switch in between. The university network still recognises the Tracker Control PC as authorized to communicate with the tracker system. Aside from this, the tracker Control PC can now communicate with the robot by communicating to it directly, bypassing the blocks imposed by the university network. An overview of the new network setup that was used during this study is shown in Figure 4.

While a change to the networking setup allowed a single PC to communicate to both the robot and tracker system, there was still a problem with communication. Control of the tracker system needed
to be done through Vizard (a specialized version of Python with severely limited access to packages), while communication to the robot needs to be done using a secure shell (SSH) connection.

To solve this mismatch of communication over SSH and communication using the Vizard Python package, Python needed to be able to send SSH commands. Since the default windows SSH functions could not be enabled due to limitations imposed by university-wide IT systems, and SSH packages for python could not be installed due to limitations of Vizard, another means of starting an SSH connection was needed. Code was written for Python to access the windows command prompt and start Putty (a common SSH program that can run from command prompt). This was used to send SSH commands to the robot via Putty.

To make this more user-friendly, a dashboard was created that gave an overview of tracking system, and a textbox with button where commands can be written and send to the robot. As part of controlling the trackers and controlling the robot, this dashboard also kept track of what trial is running and storing all collected data from the trackers (Figure 5).

![Figure 5. Tracking system dashboard. Shows locations from the tracker system, a textbox and two buttons to send commands to the robot, and buttons for supporting some secondary functions.](image)

**Measurements**

The experiment consisted of thirty-six trials per participant. After each trial, subjective measures of comfort and effort were determined using a survey. This survey consisted of two questions: “How comfortable did you feel during the last encounter?” and “How much effort did it cost to prevent collision with the robot?” rated on a 7-point Likert scale (resp. very comfortable – very uncomfortable and very effortless – very effortful).
Furthermore, the demographic questions “What is your age?”, “What is your gender?”, “Do you have experience with robots? Please explain what experience you have and please describe the robot.” were asked before the experiment started.

Additionally, the robot was fitted with six trackers and the participant wore a hat with two trackers, as shown in Figure 6. X and Y location of both the participant and robot were tracked at approximately 20 Hz using the trackers. This was converted into the walked paths and speeds and the distance between the human and robot during the trial.

![Figure 6. Robot and participant with location trackers.](image)

**Raw data to measurements variables**

The data obtained from the location trackers returned the location of the trackers placed on six spots on the robot, and two spots on the tracker hat given to the participant. At times, one or more of the trackers could not be measured by the tracking system (due to line of sight being blocked). The data was transformed into the location and orientation of the centre of the human and robot. For the human, the middle point between the two trackers was used to find the centre, and the rotation of the trackers relative to each other was used to find the orientation. When one of the trackers could not be located, the measurement at this timestep was skipped. For the robot, the orientation was determined first. This was done by determining the rotation between each set of two trackers and finding the orientation between the two points. If a tracker was missing, the sets it belongs to were skipped. The individual orientations were transformed to complex numbers, so they could be averaged into a single orientation. Using the final orientation of the robot, the location of the middle of the robot was determined for each individual tracker. This was then averaged to get the final location of the centre of the robot.

Location trackers attached to the human and robot retrieved their position with a frequency of at least 20 Hz. There was no maximum frequency set, and higher frequencies up to 60 Hz are reached during the trial.

**Procedure**

Upon arrival, participants were asked to disinfect their hands to adhere to COVID-19 regulations. They were then welcomed into the reception area, a small room leading up to the lab. COVID-19 regulations also stipulated that participants had to register their arrival by completing registration on a computer. Participants read and signed an informed consent form.
After registration was completed, participants were invited into the lab. Before starting the experiment, participants were asked to answer a few demographic questions. The experiment leader then explained the experiment. Participants were asked to move towards the goal in a manner that feels comfortable, by following a straight path, or by deviating from a straight path. They could walk at any speed they felt comfortable with and change speed or stop as desired. After arriving at the end location, participants completed a questionnaire consisting of two questions at the designated laptop. During this experiment, the participant wore a hat with two sensors on it. Participants were made aware of a big red button on the front of the robot that could be used to stop the robot. At the start of each trial, participants heard an auditory signal, after which had to start walking. Each unique condition of the experiment is done three times, for a total of 36 trials. When the trials where done, the participants were debriefed, thanked, and paid. The complete procedure took about 45 minutes.

Results
Data preparation
Data for participants 8, 19, and 22 is incomplete due to errors with the tracking system. For participant 8, robot movement data is missing for the first three trials due to an unknown cause. For participant 19, a faulty connector disabled tracking of the participant on multiple trials. Additionally, due to an unknown cause, robot movement data of participant 19 is missing. For participant 22, a faulty connector disabled the trackers on the participant for the first five trials. Out of all 24 participants, data from these three participants was dropped. Trial 1 of participant 2 was also dropped from the data, as the participant stopped half-way into the trial due to a run-in with the robot and the trial was not completed. Other data from this participant was not dropped, as comfort ratings or the walked path cannot be considered outliers.

Data exploration
Before starting the hypothesis testing, the data of the walked paths of the participants was explored.

In Figure 7, the path of a single participant is shown as an example. The analysis was based on the complete dataset.
Figure 7. Path taken by the participant. In total 12 unique conditions are shown: the four different robot paths at three different speeds. Each condition was repeated three times, and thus each graph contains a total three different paths the participant took during the condition. The path of the participant is shown in red when the participant went in front of the robot, and in blue when the participant went behind the robot. The participant walked from the right to the left. The black lines indicate the robot path, the robot moved from the top to the bottom. The figure shows data up until the point in the trial when either the robot or the participant reaches their endpoint.

Passing in front of the robot

Visually inspecting Figure 8 suggests a difference in whether participants pass in front or behind the robot, depending on the path the robot takes. A difference in if the participants go in front of the robot or behind the robot based on the speed is not visible. Figure 8 illustrates who passed first during the experiment.

Figure 8. Bar graphs showing the percentage of all trials where the participant passed in front of the robot. Graph a) shows the data split for the different robot paths, while graph b) shows the data split for the different speeds.

To evaluate if the participant passing in front of the robot was related to robot path, a Pearson’s chi-square test was done. There is a statistically significant correlation between the robot path and if the
participant passed in front $\chi^2(3, N = 756) = 238.66, p < .01$. The participant going in front of the robot was not significantly correlated to the speed of the robot ($p > .05$).

**Paths of participants**

Visually inspecting participant paths shows that there are multiple identifiable paths or strategies taken by the participants. At least four relatively well-defined ones can be identified: walking in a straight line, arching in front of the robot, arching behind the robot, and waiting for the robot to pass. These paths are shown in Figure 9.

![Figure 9](image)

*Figure 9.* Typical examples of participant paths. Each condition was repeated three times, and thus each graph contains a total three different paths the participant took during the condition. The participant path is shown in red when the participant went in front of the robot, and in blue when the participant went behind the robot. The participant walked from the right to the left. The black lines indicate the robot path, the robot moved from the top to the bottom. The figure shows data up until the point in the trial when either the robot or the participant reaches their endpoint. a) the participant walks in a straight line, in b) the participant arches in front of the robot, in c) the participant arches behind the robot, and in d) the participant waits for the robot to pass.

While the paths from these examples are clear and well defined, there were also trials where this was not the case. Other paths or strategies can be found, such as a path that combines two of the identified paths, the participant starts walking at an angled straight line from the start before arching in front of the robot, or the paths where the strategy strongly changed during the trial. These examples are shown in Figure 10.

![Figure 10](image)

*Figure 10.* In a) the participant followed a path that is a combination of arch in front of robot and walk straight: the participant walked a path that was straight initially but did so at an angle. Only when the robot path was passed, and the end point got close the participant changed their trajectory. In b) it can be observed that the participant completely changed their path during the trial. The participant seems to on trajectory to go in front of the robot but changed their path and went behind the robot.
Hypothesis A: Comfort increases with larger minimum distances between the human and robot during crossing situations.

Data preparation
For each datapoint in the trials, two vectors were created. The first vector is a human-robot vector starting at the participant and pointing to the robot. The second vector is a unit vector that represents starting at the participant and pointing in the participant moving direction. Note that this is moving direction can be different from the gaze direction. The vectors are transformed such that a with distance $r$ and angle $\alpha$ vector pointing from the human to the robot is determined. The distance indicates the distance between human and robot, and the angle indicates the rotation from the human to the robot. The results for all trials from participant 1 are shown in Figure 11.

Visualization

![Figure 11. Distance between participant and robot at different angles. The participant is depicted by the arrow in the middle. Red datapoints are from trials where the participant went in front of the robot. Blue datapoints are from trials where the robot went in front of the participant.](image)

In Figure 11 the trials are split up based on who passed first. Trials where the participant passed in front of the robot are red and tend to go around the participant seem to be mostly located between $-45$ degrees and $-180$ degrees, while trials where the robot passed in front of the human are blue and mostly located between $-45$ degrees and $135$ degrees.

Comfort and minimum distance
The minimum distance during each trial was determined to test for a relation between the comfort of participants and the minimum distance between the robot and participant, shown in Figure 12.
To estimate the proportion of variance in comfort related to minimum distance, a linear regression was performed. Minimum distance accounts for 6.1% of the variability in comfort, $R^2 = .061$, $F (1,753) = 48.82$, $p < .01$. The regression line has an intercept of 3.06 ($SE = 0.23$) and a positive slope of 1.49 ($SE = 0.21$). The corresponding formula is $Comfort = \text{Minimum distance} \times 1.49 + 3.06$.

The average comfort and average minimum distance for each robot path is shown in Figure 13. The graph shows differences in the means of comfort and minimum distance when grouping by robot paths. The linear relation found in the overall regression no longer applies here.

To gain more insight in comfort for different robot paths, statistical analysis on comfort per robot path is done. Figure 14 shows a comfort for each robot path.

Figure 12. Boxplot of the minimum distance in meters between robot and participant, grouped for each level of comfort.

Figure 13. The average minimum distance in meters is shown on the y-axis and the average comfort is shown on the x-axis. The bars indicate the 95% confidence interval, showing the accuracy of the means. The data is grouped by the different robot paths.

Figure 14. Boxplot of the comfort indicated by the participant, grouped by the robot paths.
A Shapiro-Wilk normality test indicated that the assumption of normality was violated for all four groups ($p < .01$). Thus, a non-parametric test is needed to determine if significant differences in comfort exist between the different paths taken by the robot.

A Friedman two-way ANOVA indicated that rankings of the different robot paths on comfort is significantly different for the four robot paths ($\chi^2_f = 111.38$, $df = 3$, $N = 176$, $p < .01$). A follow-up pairwise comparison is done using Wilcoxon signed rank test with a Bonferroni adjusted alpha of 0.013. The robot going left (Mean Rank = 1.75) ranked significantly lower than the robot going right (Mean Rank = 2.50, $p < .01$, $r = .50$), the robot stopping (Mean Rank = 2.75, $p < .01$, $r = .63$) and the robot going right (Mean Rank = 2.99, $p < .01$, $r = .67$). The robot going towards the right was furthermore ranked significantly lower than the robot stopping ($p < .01$, $r = .19$) and the robot going straight ($p < .01$, $r = 0.24$). The difference in ranking between the robot going straight and the robot stopping was not significant ($p = .09$, $r = .12$).

Hypothesis B: Comfort is higher when the robot moves at lower speeds around the participant.

Figure 15 shows human comfort at different robot speeds.

![Boxplot of comfort](image)

**Figure 15.** Boxplot of the comfort indicated by the participant, grouped by the different robot speeds.

A Shapiro-Wilk test of normality indicated that the assumption of normality was violated for all three groups ($p < .01$). A Friedman two-way ANOVA indicated that rankings of the different paths on comfort is significantly varied for the three speeds of the robot ($\chi^2_f = 72.17$, $df = 2$, $N = 240$, $p < .01$). A follow-up pairwise comparison is done using Wilcoxon signed rank test with a Bonferroni adjusted alpha of 0.017. Comfort at a speed of 0.85 m/s (Mean Rank = 1.64) significantly ranked lower than at a speed of 0.70 m/s (Mean Rank = 2.09, $p < .01$, $r = .41$) and at a speed of 0.55 m/s (Mean Rank = 2.27, $p < .01$, $r = .47$). Differences in ranking on comfort between a speed of 0.7 m/s and 0.55 m/s where not statistically significantly different ($p = .04$, $r = .13$).

Figure 16 combines the minimum distance into the previous findings. No additional effect of speed on minimum distance becomes apparent.
Figure 16. The average minimum distance in meters is shown on the y-axis and the average comfort is shown on the x-axis. The bars indicate the 95% confidence interval, showing the accuracy of the means. The data is grouped by the different robot speeds.

Hypothesis C: Humans will feel more comfortable when the path length of the human is shorter or equal to the path length of the robot.

The robot followed a long path of 3.72m ($SD = 0.05$) when the robot went to the left or right, or a short path of 3.24m ($SD = 0.03$) when the robot went straight or stopped. The difference in comfort for the robot path lengths is shown in Figure 17. Note that there is not necessarily a direct relation between the two measures.

Figure 17: Boxplot of human comfort and robot path length in meters.

A Mann-Whitney U test indicates that comfort is significantly lower when the robot takes the short path than when the robot takes the long path ($p < .01$). The path lengths of the participants grouped by comfort is shown in figure 18.
The data does not follow a normal distribution and contains multiple outliers. This cannot be reduced sufficiently using a logarithmic transformation. Thus, a two tailed Kendall’s Tau-B test is used to test for a correlation between the participant path length and comfort. Kendall’s Tau-B’s test indicates that there is a significant negative correlation between the participant path length and comfort, \( \tau = -.167, p < .01, N=756 \). Visual inspection of the graph suggests that a comfort rating of 1 or 2 is associated with a longer participant path length, while a comfort rating of 7 is associated with a shorter participant path length. Each comfort rating occurred in at least 5% of the trials, the full distribution is shown in Appendix A.

The path length difference between the robot and participant is determined by subtracting the robot path length from the participant path length. This data is skewed and has multiple outliers. The data is transformed by taking the base 10 logarithm, as this can improve data quality for data with a clear minimum but no maximum. This results in less skewed data and a reduction in the number of outliers. Figure 19 shows a boxplot of the transformed path length difference and comfort.

A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by the logarithm of the difference in path length. Logarithm of the difference in path length accounts for a variability of 0.6% of comfort, \( R^2 = .006, F (1, 753) = 4.91, p = .03 \). The regression line has an intercept of 4.83 (SE = 0.12) and a negative slope of -0.53 (SE = 0.25). This corresponds to a regression formula of \( Comfort = -0.53 \times \log_{10}(\text{path length difference}) + 4.83 \).

Another measure that can be used to examine the path of the participant is the deviation from a straight path which is a measure of how far a participant moves away from a path that goes in a straight line between the start and the goal. This data is skewed and has many outliers. Transforming the data by taking the base 10 logarithm from the deviation from path makes for less skewed data, and the number of outliers is reduced. Figure 20 shows a boxplot of the transformed deviation from path and comfort.
A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by logarithm of human deviation from path. Logarithm of deviation from path accounts for a variability of 0.6% of comfort, \( R^2 = .006, F (1, 753) = 18.23, p = .04 \). The regression line has an intercept of 4.3 (SE = 0.17) and a slope of -0.52 (SE = 0.25). This corresponds to a regression formula of

\[
\text{Comfort} = -0.52 \times \log_{10}(\text{deviation}) + 4.3.
\]

To gain insight in these different measures of the walked path, the correlation between them was tested. There is a large and positive correlation between the logarithm of difference in path length and the human path length, \( r (753) = .70, p < .001 \) and a medium-large and positive correlation between the logarithm of difference in path length and the logarithm of deviation from path, \( r (753) = .44, p < .001 \).

Additional figures and analysis

Additional figures for Figure 15 to 20 are can be found in Appendix A. This includes bar graphs to identify changes more easily in the means and this includes extra boxplots for the graphs with transformed data.

Additional figures and analysis grouped by robot paths can be found in Appendix B. A statistically significant linear relation between comfort and minimum distance between robot and participant is found for the robot path left condition (\( R^2 = .156, F (1, 185) = 34.15, p < .001 \)), and the robot path right condition (\( R^2 = .093, F (1, 189) = 19.36, p < .001 \)). Using a Bonferroni corrected alpha of 0.0125, no statistically significant linear relation is found for the robot path stop and robot path straight conditions. Additionally, a statistically significant correlation between comfort and human path length is found for the robot path left condition, \( r = -3.51, p < .001 \). Using a Bonferroni corrected alpha of 0.0125, no statistically significant correlation has been found for the robot path stop, the robot path straight and robot path right conditions. Finally, using a Bonferroni corrected alpha of .0125, no statistically significant correlation between human deviation from path and comfort has been found for any of the robot path conditions.

Additional figures and analysis grouped by whether the robot or human passed in front can be found in Appendix C. A statistically significant linear relation has been found between comfort and minimum distance between human and robot when the robot passed in front of the human (\( R^2 = .043, F (1, 372) = 16.45, p < .001 \)) and when the human passed in front of the robot (\( R^2 = .103, F (1, 379) = 43.49, p < .001 \)). Furthermore, a negative correlation is found between path length difference and comfort when the robot passed in front, \( r = - .20, p < .001 \), and a positive correlation is found between path length difference and comfort when the human passed in front, \( r = .11, p = .002 \). Note the opposite effects in path length difference when the human passed in front compared to when the robot passed in front. While a statistically significant correlation is found between human path length and comfort
when the robot passed in front of the human, $r = -.31$, $p < .001$, no correlation is found when the human passed behind the robot, $r = -.07$, $p = .066$. Finally, no correlation between human deviation from path and comfort is found when the human passed in front of the robot or when the robot passed behind the human.

**Discussion**

To answer the research Question “What does a comfortable human-robot crossing scenario look like?”, An experiment containing several human-robot crossing scenarios was created, and measures on the human path and comfort where determined. These measures have been analysed, and the results showed that the paths taken by human during a crossing scenario can be categorised into several paths. The four categories that could be identified are: a straight-line path, a path arching in front of the robot, a path arching behind the robot, and a path that stops for the robot is identified.

Results showed that several human paths can be identified and classified, but that there is no good manner to classify all crossing scenarios. It was also found that who passed in front, a measure that partly classifies the human path, moderates the relation between the human path and comfort. This measure is influenced by the robot path, but not by the robot speed. More moderation measures might appear when paths can be fully classified. Thus, research towards a precise method to classify the paths is beneficial, as there are paths where it is still unclear on how to classify them without a proper classification method. Fuzzy membership functions could be a solution, as it might be beneficial to reduce the number of classified paths to get more easily interpretable data.

When not taking differences per trial into account, there is a linear relation between human comfort and the minimum distance between human and robot. A similar effect was found by Neggers et al. (2018).

The average comfort rating varies based on the robot path. This is no surprise, as previous studies already found that people have a preference on paths when crossing others (Oliver et al., 2012). Some robot paths are associated with a higher comfort and longer minimum distance than others, but this relation is not linear. The relation between minimum distance and comfort grouped by robot paths only appears when the robot path arches to the left or to the right. Since people have control over the minimum distance to a certain extent, they might always try to keep a comfortable minimum distance but fail to do so when the robot starts a path that includes arching.

The minimum distance is considered as the total minimum distance during a trial. When having a more in-depth look at the distance between human and robot during the trial, the minimum distance is different depending on the angle between the human and robot. For example, the distance is on average smaller when the robot is to the left of the human than when the robot is to the right of the human. This could be explained by the experiment being done in an asymmetrical set-up; the robot always approaches from the right. A study on personal space at different directions confirmed that there is no difference between left and right (Neggers, Cuijpers, Ruijten & Ijsselsteijn, 2021). However, there is also a difference in the relation between minimum distance and comfort when the robot is in front of the human compared to when the robot is behind the human; when the human passes in front of the robot the correlation between minimum distance and comfort is higher than when the robot passes in front of the human. This effect might be related to the effect of higher average comfort at higher minimum distances found in human-human interactions (Gérin-Lajoie et al., 2005) and findings in human-robot interactions (Neggers, Cuijpers, Ruijten & Ijsselsteijn, 2021). Due to this, what robot path is most comfortable is likely based on the angle the robot approaches at. To improve on
the findings in this study, this effect of direction should be studied in more detail, by setting up a similar experiment but with more angles from which the robot approaches.

The results showed that human comfort is lower at higher robot speed. Humans feel less comfortable at a speed of 0.85 m/s than at speeds of 0.70 m/s or 0.55 m/s. However, there seems to be a floor effect as no difference was found between the speeds of 0.70 m/s and 0.55 m/s. To find when this floor effect occurs exactly, or what speeds are deemed comfortable, a follow-up study needs to be conducted with more different speeds. Due to the maximum robot acceleration, a study on speeds above 0.85 m/s would need to be conducted in a bigger and different setup or with a different robot.

Human comfort is higher at shorter path length differences and human comfort is lower at longer path length differences. This is in accordance with expectations based on Silva et al. (2018). Furthermore, human comfort is higher at a short robot path length and lower at a long robot path length, comfort is also higher at shorter human path lengths compared to longer human path lengths, and comfort is higher at bigger deviations from path compared to smaller deviations as well.

However, the found effects do not hold within the individually different robot paths. A correlation between comfort and human path length when the robot patch arches left exists, but for the other robot paths the correlation between comfort and human path length and the correlation between comfort and deviation does not exist. An explanation as to why the correlation only exists when the robot arches left is that this is the least comfortable robot path in general, and since the robot seems to approach the human there is less control for the human to follow a path and speed that ensures a comfortable crossing situation.

When grouped by robot path, results of correlation tests for human path length are identical to results for robot path condition since they are the same variable shifted by a constant.

While an overall effect is found that the path the human follows is related to comfort, no measure that correctly identifies this for all robot paths is found. It is interesting that the correlation between path length difference and comfort has an opposite effect depending on whether the human or robot passes first. This might be due to people following different paths or having a different preference for a path depending on who passed first. To get more insight into this, classification of the paths could be very beneficial. These opposite effects could also explain why effects have not been found within the robot path conditions, as the effects within the condition might have been cancelled out.

Since path length difference, human path length, and deviation from path are all measures that describe the path walked by the participant, it would thus explain why those measures are related to comfort in the same direction with approximately the same order of magnitude. However, when doing more in-depth analysis, differences between the measures do occur. This study has focused on difference in path length, but there can be advantages to using another measure such as deviation from path due to the ease of use. However, it is important to keep in mind that the measures give different results depending on the exact analysis performed.

**Conclusion**

The current study found that comfort increases with larger minimum distances between a human and robot. To be able to make human-robot crossing scenarios more comfortable, robots should keep a certain minimal distance from humans or allow humans to keep this distance. Furthermore, results show that lower robot speeds are more comfortable for humans. Somewhere between 0.70 m/s and 0.85 m/s a negative effect of speed on comfort occurs. Thus, a robot should move at speeds below 0.70 m/s for an optimal comfort.
Regarding the paths taken during crossing scenarios, it is found that difference in path length is related to comfort and can be used as a predictor for comfort when also considering whether the human or robot passed first. While other measures exist that appear similar when not considering other factors, they do not perform the same in when taking these factors into account. Thus, more research into classification of paths is needed and the measures that can be derived from these paths.

These findings show what a comfortable human-robot crossing scenario looks like, it provides a step towards designing more comfortable human-robot crossing scenarios, and it helps guide future research.

References


Appendix A: Additional Figures

Figure A1: Extra figure with the amount of datapoints at each comfort level for Figure 12, 19, and 20.

Figure A2: Extra figure corresponding to Figure 12. a) boxplot of the minimum distance in meters between robot and participant, grouped for each level of comfort. b) shows the means of minimum distance between robot and participant with 95% CI.

Figure A3: Extra figure corresponding to Figure 13. a) shows a boxplot of the comfort indicated by the participant, grouped for the different robot paths. b) shows the means of the comfort with a 95% confidence interval.
Figure A4: Extra figure corresponding to Figure 15. a) shows a boxplot of the comfort indicated by the participant, grouped for the different robot speeds. b) shows the means of the comfort with a 95% confidence interval.

Figure A5: Extra figure corresponding to Figure 16: a) shows a boxplot of human comfort and robot path length. b) shows the means of comfort with a 95% CI.

Figure A6: Extra figure corresponding to Figure 17. Difference in path length of robot and participant grouped per comfort level. a) shows the data normally, b) shows log10 of the path length.
Appendix B: Results split by robot paths

To gain more insight in the results and the implications of the results, additional analysis has been done grouped by the different robot paths.

A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by minimum distance in the stop condition. No statistically significant linear relation is found ($p = .850$).

A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by minimum distance in the stop condition. Logarithm of deviation from path accounts for a variability of 0.6% of comfort in the stop condition, $R^2 = .156$, $F (1, 185) = 34.15$, $p < .001$. The regression line has a no significant intercept ($p = .859$) but a slope of 3.15 (SE = 0.54).

This corresponds to a regression formula of $\text{comfort}_{\text{stop}} = 3.15 \times \text{min.dist}$. 

Figure A7: Extra figure corresponding to Figure 18. participant deviation from a straight path grouped per comfort level. a) shows the data normally, b) shows log10 of the deviation.

Figure B1: Boxplot of comfort and minimum distance between the robot and participant for the robot path stop condition

Figure B2: Histogram of comfort for the robot path stop condition

Figure B3: Boxplot of comfort and minimum distance between the robot and participant for the robot path left condition

Figure B4: Histogram of comfort for the robot path left condition
A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by minimum distance in the straight condition. After accounting for a Bonferroni corrected alpha of 0.0125 no significant linear relation is found $R^2 = .022$, $F (1, 187) = 4.16$, $p = .043$. The regression line has an intercept of 4.25 (SE = 0.42) and a slope of 0.90 (SE = 0.44).

A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by minimum distance in the right condition. Logarithm of deviation from path accounts for a variability of 9.3% of comfort in the right condition, $R^2 = .093$, $F (1, 189) = 19.36$, $p < .001$. The regression line has an intercept of 3.28 (SE = 0.36) and a slope of 1.63 (SE = 0.37). This corresponds to a regression formula of $comfort_{right} = 1.63 \times min.\ dist. + 3.28$.

Correlation tests using Kendall’s Tau-B were performed. No correlation is found between human path length and comfort in the stop condition, $p = .161$ and no correlation is found between human deviation from path and comfort in the stop condition, $p = .572$. 
Correlation tests using Kendall’s Tau-B were performed. A negative correlation is found between human path length and comfort in the left condition, \( r = -3.51, \ p < .001 \), but no correlation is found between human deviation from path and comfort in the left condition, \( p = .322 \).

Correlation tests using Kendall’s Tau-B were performed. No correlation is found between human path length and comfort in the straight condition, \( p = .981 \) and no correlation is found between human deviation from path and comfort in the straight condition, \( p = .315 \).

Correlation tests using Kendall’s Tau-B were performed. No correlation is found between human path length and comfort in the left condition, \( p = .109 \), and after accounting for a Bonferroni corrected alpha of 0.0125 no correlation is found between human deviation from path and comfort in the left condition, \( r = .11, \ p = .030 \).
Appendix C: Results split by passing in front or behind

A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by minimum distance when the robot passes in front. Logarithm of deviation from path accounts for a variability of 4.3% of comfort in the stop condition, $R^2 = .043$, $F (1, 372) = 16.45$, $p < .001$. The regression line has an intercept of 3.40 (SE = 0.32) and a slope of 1.29 (SE = 0.32). This corresponds to a regression formula of $comfort_{robotInFront} = 1.29 \times \text{min.dist.} + 3.40$. 
A regression analysis is performed to estimate the proportion of variance in comfort that can be accounted for by minimum distance when the human passes in front. Logarithm of deviation from path accounts for a variability of 10.3% of comfort in the stop condition, $R^2 = .103$, F (1, 379) = 43.49, $p < .001$. The regression line has an intercept of 2.42 (SE = 0.37) and a slope of 2.06 (SE = 0.31). This corresponds to a regression formula of $\text{comfort}_{\text{HumanInFront}} = 2.06 \times \text{min.dist.} + 2.42$.

Correlation tests using Kendall’s Tau-B were performed. A negative correlation is found between path length difference and comfort when the robot passed in front, $r = -.20$, $p < .001$, while a positive correlation is found between path length difference and comfort when the human passed in front, $r = .11$, $p = .002$.

Correlation tests using Kendall’s Tau-B were performed. A negative correlation is found between human path length and comfort when the robot passed in front, $r = -.31$, $p < .001$, but no correlation is found between human path length and comfort when the human passed in front, $r = -.07$, $p = .066$. 
Correlation tests using Kendall’s Tau-B were performed. No correlation is found between human path deviation and comfort when the robot passed in front, $p = .16$, and no correlation is found between human path deviation and comfort when the human passed in front, $p = .316$. 