

A Visual Method for Robot Proxemics Measurements

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ABSTRACT

Human interaction knows many non-verbal aspects. The use of space, among others, is guided by social rules. Not conforming to these rules may cause discomfort or even miscommunication. If robots are to interact with people, they must follow similar rules. The current work tries to identify factors that influence human preferred interaction distance in conversation-like interaction.

For the measurement of interaction distances an accurate and objective visual method is presented. In this method, the researcher does influence the results by disturbing the interaction.

It is found that subjects choose interaction distances comparable to those in human interaction. Variations are mostly explained by subject age and, depending on age, by gender or robot appearance. This is the first time, to our knowledge, that a clear age and gender effect is found in human-robot interaction-distance.

Categories and Subject Descriptors

I.4 [Computer Applications]: Social and behavioral sciences — *Psychology*; I.2.9 [Artificial Intelligence]: Robotics — *Commercial robots and applications*; H.5 [Information Systems]: Information Interfaces and Presentation (e.g., HCI) — *Benchmarking*

General Terms

Measurement, Experimentation, Human Factors

Keywords

Proxemics, Human-Robot Interaction, Visual Measurement

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1. INTRODUCTION

Advancements in artificial intelligence enable the creation of more intelligent robots that can perform a greater array of tasks, making it more realistic and even desirable to bring them into the house or office. People are social beings however, and human interaction is guided by social rules. While people can learn to adapt to robots, the robots should be made to follow similar rules that will make the interaction natural and require no extra effort on the human part. The current research tries takes an approach from the sociological concept of proxemics.

Recent research has indicated the influence of robot appearance [?], subjects’ personality [?] and type of interaction on the interaction distance. The typical setups of those experiments were inside the laboratories, where colleagues/volunteers got clear assignments about the type of interaction that should be started. The research reported here is performed in a free setting during an arts and technology festival, with the subjects unaware of the experiment performed. This resulted in a large number of interactions, with variety in age and gender which is difficult to reproduce in robotics laboratories.

1.1 Proxemics

The field of proxemics is concerned with interpersonal distance and personal space. The term was coined by the anthropologist Edward T. Hall in his 1966 book *the hidden dimension*. In this book, Hall uses findings from the animal kingdom and insights in human experience of space to define four personal spheres. These spheres define areas of physical distance that correlate reliably with how much people have in common (cultural difference). Where the boundaries of these spheres exactly lie is additionally determined by factors such as gender, age and culture [?, ?, ?]. When one comes too close to another, the other may feel crowded or intimidated. If, on the other hand, one stays too far back, this is seen as awkward and one may be perceived as cold or distant. Appropriate distances found by Hall in western culture for adults of both genders are displayed in Table 1.

1.2 Human Interaction

To explain the locations of these boundaries, Hall theorizes that they coincide with the boundaries of sensory shift. At different distances, touch, vision, hearing but also smell may be optimal, distorted, or not available at all. Physical properties also come into play, such as an arm’s length, which defines the distance from where one can touch the other, or two arms’ length, which defines the boundary

Table 1: The four spheres of physical distance corresponding to cultural difference according to Hall.

Designation	Specification	Reserved for ...
Intimate distance	0 - 45 cm	Embracing, touching, whispering
Personal distance	45 - 120 cm	Friends
Social distance	1.2 - 3.6 m	Acquaintances and strangers
Public distance	> 3.6 m	Public speaking

where interaction partners can cooperate to make physical contact [?].

1.3 Human-Robot Interaction

In proxemics studies, the focus lies on human-human interaction. However, when one interaction partner is a robot, it is not well known to what extent the different factors of human proxemics still apply and what new factors play a role. Moreover, since robots typically do not have an odor or body heat, sensory input can no longer explain or predict appropriate distances, even if the limitations on vision and hearing may still apply.

While human-robot proxemics may follow a similar pattern as human and animal proxemics in having distinct zones, no assumptions about such existence or the locations of possible boundaries are made in the current research. Instead, the focus is to identify factors that influence interaction distance and their effect. In Section 1.4, a list is presented of such possible factors, all of which were included in the empirical study. Along with the description of each factor, a rationale to include it is given. Factors that were not included were factors that are irrelevant for a robotic interaction partner, such as body heat or smell.

1.4 Included Factors

Robot type could count towards the cultural difference equivalent of human-robot interaction. People may prefer to interact with a robot with which they have more in common or with which interaction is easier due to the height and shape. This would translate into more frequent observations of interaction with a certain robot, but may also influence the preferred distance. Specifically robot height and shape was investigated.

Although Hall doesn't mention **subject height** as a factor, there are studies that do take it into account because height difference influences face-to-face distance [?]. In addition, when adjusting a screen or monitor, appropriate height and orientation are meant to achieve a neutral neck position and minimal neck movement at the optimal viewing distance. Since subjects had no control over screen height and orientation, they might have chosen a different distance instead to view the screen at a more comfortable angle.

Since **subject gender** is an important factor in human proxemics [?, ?], it may also play a role in human-robot proxemics. This point is complicated by the fact that the robots used in this experiment represented a person whose gender might be of influence. The operator's gender was left out of consideration however, since the operator's gender was only obvious for the Mobi Sr. robot, and its operator could change at any time (see Sections 2 and 3.1). Since the measurements are pooled, any gender effects found would then

represent how men's and women's preference are different in regard to a genderless robot.

Subject age is a factor in human cultural difference and therefore in human proxemics [?, ?], thus it might also be of influence in human-robot proxemics. The same complication as with the operator's gender arises, and it is disregarded on the same grounds.

When the location of interaction is **crowded** with people, it may be impossible for a subject to keep the preferred distance since doing so might bring him or her undesirably close to one or more other people. Since only the upper bound of distance options is limited, subjects are forced to stand closer to the robot. However, in such a situation the subject is also forced to stand closer to other humans. It would be interesting to see how the subject resolves this shortage with respect to the relative amount of distance the subject gives up to the robot and other humans.

1.5 Hypotheses

Based on the inclusion rationales for each factor, we formed the following hypotheses:

- Children prefer the smaller robot, which means more observations with it and smaller distance compared to Mobi Sr.
- Height difference between subject and robot causes greater distance.
- Men will stand closer because of affinity for technology
- Younger people will stand closer as they do in human interaction [?].
- Spatial constraints caused by crowding cause smaller distance.

2. MATERIALS

Two robots were used in the current experiment. They could be controlled by volunteers through a desktop computer to which the robots were connected via a wireless network.

2.1 Robot 1: Mobi Sr

The first robot, called Mobi¹ Senior (Figure 1), was approximately 175 cm tall and had a round base with a diameter of 66 cm with semi spheres sticking out to cover the support wheels. It was driven by two wheels left and right of the centre of the base, and balanced by 4 passive wheels around the base. The robot was not made to resemble human form. In spite of this, it was intended to be a communication device. It was equipped with a monitor which was mounted at the top of the robot at eye level. This monitor showed a video feed that was sent from a webcam at the operator's computer showing the operator's head and shoulders, as is typical for a web conference. The robot had a webcam mounted directly above the robot's monitor allowing the operator to view the remote location. In addition, the robot had stereo speakers and a microphone, and the operator's computer had a stereo headset and a microphone as well, enabling two-way audio communication between the operator and an interaction partner. The operator could move the robot back and forth and rotate it left or right around its axis by using the arrow keys on the local keyboard.

¹Mobile Operated Bi-directional Interface



Figure 1: Two people interacting with Mobi Sr.

2.2 Robot 2: Mobi Jr

A second, smaller robot was used called Mobi Junior (Figure 2). It had many of the same features as Mobi Senior, with the most notable exceptions of lacking a monitor to show the operator, and being only 112 cm tall. It had a square base with rounded edges and was 60 cm wide and deep. In addition, Mobi Junior's operator also had camera controls to aim the camera anywhere between 28 deg up and 25 deg down. Its shape was quite different, but apart from this, Mobi Junior also had stereo speakers and a microphone, allowing the same two way audio communication, and a webcam mounted in a round head to allow the operator to see the remote location. Mobi Junior was designed to appeal to children, who might have trouble seeing the monitor on Mobi Senior and who would be too short to be seen by its camera, or who might be intimidated by such a tall mobile device.

3. METHODS

3.1 Setting

The robots were showcased during a three day arts and technology festival. This festival was held in a former factory and covered three large halls. There was a stand belonging to the Mobi team where visitors could volunteer to operate either robot. There were two large screens at the stand facing the hall where visitors could see the video feeds from the robot cameras. Both robots could be directed to any location within the halls from the stand through a local wireless network. Visitors were free to take control of the robots or to interact with them. People from the Mobi team were present at the stand to give information about the robots and instructions on how to control them, and at the robots' locations to answer any questions.

3.2 Procedure

To determine the appropriate distance the robots would



Figure 2: A girl interacting with Mobi Jr. and two bystanders (faces have been blurred).

need to keep, measurements were made on the distance to the robots that people voluntarily chose in different situations. A prospective observational design was chosen to ensure ecological validity. All approaches were voluntary and without knowledge of the experiment. Volunteer operators were not instructed to stop moving the robot during interaction with people, but consistently did so. Interactions were not included until the interaction was established and the robot had stopped. Digital photographs were taken of interactions and were analyzed later (see Section 4.4). Subjects were included more than once only if they were observed in different situations with respect to crowdedness, and only once per crowdedness category (see below). Photographs typically showed several people each, sometimes in a small crowd. It was not unusual to have more than one interaction per photograph, with a maximum of five. Out of all taken photographs, 72 were used for distance measurement, depicting 106 subjects in 140 observations.

Additionally, frequencies were collected of observed interactions between age group and robot type. Subjects were included only once, even if they were included more than once in distance measurement. Photographs that were unsuitable for distance measurement could be included in this tally if the pictured subject was not yet seen in the distance measuring photographs and if the interaction met the previously stated requirements. For age group/robot type frequencies, 135 unique subjects were counted.

Because of the observational nature of the experiment, subjects were not approached by the researcher to fill out any questionnaires. Therefore, subject length had to be measured on the photograph (see Section 4.4) and subject age was estimated. Because of the imprecise nature of estimation, age was restricted to four categories shown in Table 2.

4. METRICS

4.1 Interaction

Observations were included if a subject directly interacted with the operator or the robot. For Mobi Sr. this could include talking with and waving or gesturing at each other.

Table 2: Age categories used in the proxemics experiment

Category	Ages	Notes
Children	0 - 11	Subjects predate puberty
Teenagers	11 - 19	
Young Adults	19 - 30	Subjects are typically students
Adults	> 30	

Even though subjects could not see the operator on Mobi Jr., waving at or touching the robot was also considered direct interaction. Observations were also included if another person interacted directly with the robot while the subject stood in front of the robot and faced it in a way that the subject too could interact with it, either through conversation or gesturing.

4.2 Crowdedness

Crowdedness was quantified with Hall’s four spheres of personal distance in mind. It is determined as the biggest sphere in which the subject may choose to stand while still being able to interact with the robot. The actual distance the subject chooses can be classified at most as this sphere, or a smaller one. This is a per-subject classification which means that subjects in the same photograph may be assigned to different crowdedness categories.

Interaction is blocked if a person obscures the view between subject and robot. In this case, the interaction is not counted and no crowdedness category is assigned. It is possible for several people to directly interact with the robot if they stand next to each other. In this case the interaction would cease to be direct for one subject if the subject would move away, so to maintain the same type of interaction, the subject can at most be in the sphere he or she is already in. In that case the subject’s distance directly determines the crowdedness category.

If a subject already interacts indirectly because another person stands closer without blocking the subject’s interaction, then the interaction is counted and the crowdedness category is also assigned to the actually occupied sphere.

4.3 Measured Distance

The exact measured distance is usually nose-to-nose distances [?, ?, ?]. However, since in the current experiment one interaction partner lacks a nose, another measure had to be devised. Moreover, given the utilized measurement methods, accurate measurements could only be made for distances on a given plane, more specifically the floor. For these reasons, the point where the subject stood was defined as the point on the floor directly under the centre of the subject’s torso. This point is a fair indication (though not an average) of the position of either foot and also takes leaning forward or backward into account. The measured distance was from this point to the nearest point on the robot’s shell. For the robots, no central point was defined because their shells created a perimeter that could not be crossed, thereby defining a suitable minimum distance. Human beings on the other hand can stand over smaller objects, which can be expressed in the chosen scheme. In addition, neither robot could lean, so no corrections would have to be applied to the perimeter.

Note that in this scheme the measured distance is greater

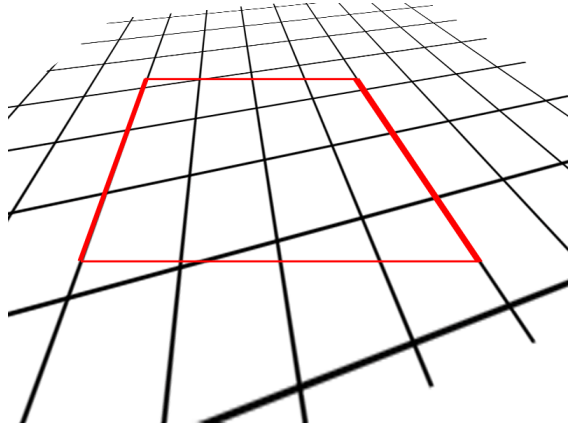


Figure 3: Parallel lines in perspective with a highlighted trapezoid constructed from a random pair of horizontal lines and the pictured perspective lines.

than 0 if the subject’s feet are physically touching the robot’s shell. A measured distance of 0 means that the subject has placed one foot on either side of the robot’s base and is standing over it, which was theoretically possible with both robots, but only feasible with Mobi Jr. This measuring scheme gives measurements that are comparable to nose-to-nose distance for the Mobi robots. The contribution to the distance for a person standing upright will typically be almost a foot’s length too long, but the robots contribution will be too short because their heads (the round head containing the camera for Mobi Jr., and the monitor for Mobi Sr.) are receded with respect to the base, and so would have given bigger measurements if measured from where their noses might have been if they had them.

4.4 Visual Measurement

Digital photographs were used to determine the distance to the robot chosen by the subject, subject height and the distance between the robot and the nearest person relevant to determine the crowdedness category. All photographs pictured the entire robot and the entire subject. If possible, the photograph was taken from a position perpendicular to the line between subject and robot.

In photographs where the subject and the robot were in a plane parallel to the camera’s focal plane, perspective distortion was not an issue and distance measurement was very similar to the method used in [?]. Since all the measurements from the robot were known, a ratio between pixels and centimeters could easily be established. This ratio then related pictured lengths to actual lengths, with which subject distance and height could be measured. At the resolution the photographs were taken, robot height measurements ranged from about 600 to 2700 pixels, but would typically be around 1600 pixels, giving sub-centimeter precision for size measurements and distance measurements without a perspective element.

Even though no markings were applied, the floors in the former factory halls had enough features to find a pair of parallel lines. Another pair could be freely chosen in the picture out of any pair of perfectly horizontal lines, since these are always projected parallel to the camera’s focal plane and

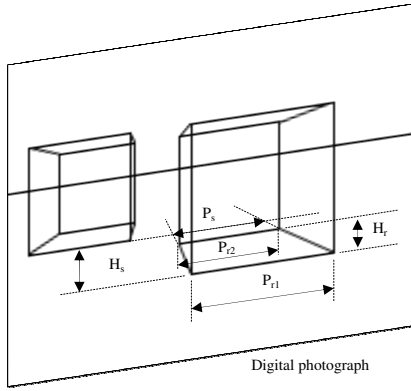


Figure 4: The reference object and the subject in a photograph.

thus to each other². The two pairs will enclose a trapezoid in perspective projection (Figure 3). The ratio between the length of the top and bottom of the trapezoid, P_{r2} and P_{r1} respectively (Figure 4) provides the amount of decrease in size due to perspective distortion over a distance D_r (Figure 5) whose projected size is given by the height of the trapezoid H_r . This ratio may also be viewed as a scale factor, giving the size of objects projected on the top line P_{r2} in relation to objects projected on the bottom line P_{r1} or vice versa, provided that they reside on the same plane, such as the floor. Using the parallel lines that follow the reference plain (the floor), such a scale ratio can be calculated for any given height, for instance H_s , in the photograph by choosing another horizontal line P_s to form the top of the trapezoid. In this way, sizes of objects on the floor can be related to one another. By relating a position to that of the robot with known dimensions, sizes such as subject height can now be measured across the entire photograph.

To obtain the distance between any two points on a plane, a known reference distance D_r is needed. This reference distance serves to quantify perspective distortion and to relate projections with a depth component to actual size. This distance would need to be perpendicular to the focal plane. If the reference object is not aligned in such a manner, then a bounding trapezoid (projection of a rectangle) can be constructed with known measurements that is aligned in this way using the image centre and Pythagoras' theorem. Let us assume furthermore that the optical axis is parallel to the floor. Now take the distance D_{r0} from the camera to the reference object. Using the object's known width w , the projection of this width on the picture plane P_{r1} and the focal distance f (the distance between the focal point and the picture plane), we could directly compute the depth distance:

$$D_{r0} = \frac{w}{P_{r1}} f \quad (1)$$

A depth distance between two points in the photograph can be expressed as a difference between two absolute dis-

²Zero roll is assumed. If any roll is determined then either the chosen lines should not be horizontal but instead follow the roll angle, or the picture should be turned upright first.

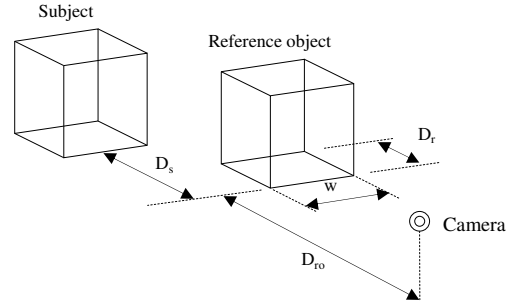


Figure 5: The reference object and the subject in the world.

tances, e.g.:

$$D_r = \frac{w}{P_{r2}} f - \frac{w}{P_{r1}} f \quad (2)$$

When expressed as a ratio of distances, the focal distance f and reference measure w are eliminated:

$$\begin{aligned} \frac{D_r}{D_s} &= \frac{\frac{w}{P_{r2}} f - \frac{w}{P_{r1}} f}{\frac{w}{P_s} f - \frac{w}{P_{r1}} f} = \frac{\frac{1}{P_{r2}} - \frac{1}{P_{r1}}}{\frac{1}{P_s} - \frac{1}{P_{r1}}} = \frac{\frac{P_{r1} - P_{r2}}{P_{r2} P_{r1}}}{\frac{P_{r1} - P_s}{P_s P_{r1}}} \\ &= \frac{P_s P_{r1} (P_{r1} - P_{r2})}{P_{r2} P_{r1} (P_{r1} - P_s)} = \frac{P_s P_{r1} - P_{r2} P_s}{P_{r2} P_{r1} - P_{r2} P_s} \end{aligned} \quad (3)$$

Where D_s is the distance between the front of the reference object and any other desired point where for example the subject might be found. If the assumption that the optical axis were parallel to the floor was violated, there would be an error in the computation of D_r . But there would be a proportional error in the calculation of D_s . Because these errors are proportional, the ratio between the two depths is still correct. Furthermore, because we use this correct ratio and our knowledge of the reference distance D_r , the computation for D_s is corrected. Because P_s is computed from P_{r1} , P_{r2} and the height differences H_r and H_s (see Figure 4), we can even cut short calculating P_s and D_r , and simplify to the following form:

$$\frac{D_r}{D_s} = \left(\frac{H_r}{H_s} - 1 \right) \frac{P_{r1}}{P_{r2}} + 1 \quad (4)$$

D_s will only provide a depth measurement though, we can combine this with a 'parallel plane' measurement to obtain a component perpendicular to the focal plane, and a component parallel to it. We can then use Pythagoras' theorem to determine the distance between any two points on the floor. Reference depth measurements (H_r) in the current experiment ranged roughly from 60 pixels to 450 pixels to capture a length of typically around 55 cm, giving almost centimeter precision or better.

5. RESULTS

140 Observations of 106 people were collected during a three day period. A Shapiro-Wilk test revealed that the

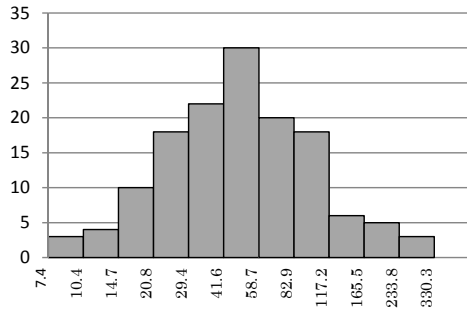


Figure 6: Observation counts per distance range in centimeters. Bin sizes increase logarithmically.

data was not normally distributed. Inspection of the data suggested a logarithmic-normal distribution, which was confirmed by a second Shapiro-Wilk test on the logarithmically transformed data. All further tests were done on the transformed data. Out of the 140 observations one outlier was removed that was more than five standard deviations from the mean. The resulting transformed dataset had a mean of 3.87 and a standard deviation of 0.74. Subtracting or adding one standard deviation from the mean and transforming back to centimeters gives a 68.3% confidence distance interval of 23 to 100 cm with a mean of 48 cm (Table 3, Figure 6).

The natural logarithm of the chosen distance was analyzed using an analysis of variance with a $2 \times 2 \times 4 \times 4$, Robot type \times Gender \times Environment \times Age group, unbalanced fractional factorial design. Since there were significant effects for Age group \times Robot type [$F(3, 124) = 6.75, p < .0005$] and Age group \times Gender [$F(3, 124) = 2.67, p = .05$], additional analyses were conducted per age group using a $2 \times 2 \times 4$ design. In no case did the environment reach significance. For children, robot type was significant [$F(1, 41) = 12.12, p = .001$]. As can be seen in Table 3, the mean distance chosen by children was 26.8 cm for the small robot and 70.4 cm for the big robot. The Gender was a significant factor for teens [$F(1, 41) = 5.00, p = .03$] and marginally significant for adults [$F(1, 7) = 5.18, p = .057$]. The difference in chosen distance between male and female was remarkably large for Adults (93.5 versus 232.9 cm), but this difference was based on a few observations. For the Young Adults neither Robot type nor Gender were not significant factors in the chosen distance.

To test if subject height had any influence, the data set was split to age, but the age groups young adult and adult were pooled, since children and teens still grow and as such subject height is not an independent factor over all age groups. Since subject height would only be meaningful relative to robot height, separate tests were performed for Mobi Jr. and Sr. The main effect and the interaction with the environment were tested. For neither robot did subject height reach significance [$F(1, 5) = 2.68, p = .15$ for Mobi Jr.; $F(1, 38) = .002, p = .96$ for Mobi Sr.], nor did the interaction with environment [$F(1, 4) = 5.49, p = .08$ for Mobi Jr.; $F(1, 35) = 2.14, p = .11$ for Mobi Sr.].

Table 3 shows the mean distance in centimeters for the significant groups. Significant groups are bold and underlined. Since means and standard deviations were computed

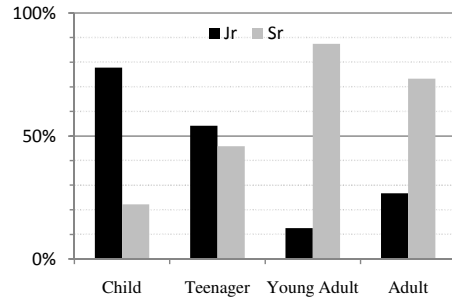


Figure 7: Observed interaction frequencies relative to robot type.

under logarithmic transformation, the distances these standard deviations represent are not equal in both directions. Therefore, the converted distances from one standard deviation below to one standard deviation above the mean centimeters are shown in brackets, providing a 68.3

Figure 7 shows the relative number of observations with each robot per age group. Since these observations are random in nature and not drawn from any distribution, no tests for significance can be performed. Children and teenagers are seen with Mobi Jr. respectively 3.5 and 1.2 times more often than with Mobi Sr. Young adults and adults are seen with Mobi Sr. respectively 7 and 2.8 times more often than with Mobi Jr.

6. DISCUSSION

All distances found in the present work except one suggest that the appropriate interaction distance for human-robot interaction lies within the personal zone of human interaction. The single divergent distance, which lies in the far phase or the social zone, is based on four observations, all of which show women watching the robot instead of talking to it. While this may be the preferred type of interaction for this group, the small number of observations is not sufficient to support this conclusion. Given the fact that this is the only incongruous result, there is reason to doubt the validity of this finding.

The personal distance found in the groups other than adult women is suitable for the type of interaction in this experiment among humans, and suggests acceptance of the robots as an agent that represents a social being. It should be noted however that in the case of Mobi Jr. it was apparent through conversations with it that people, especially children, did not always know it was controlled by a human being. In this case they could have accepted it as an autonomous agent that should be treated with similar social rules.

In the current work, the shape of the robot was only of influence on children. While this was in the line of expectation, since Mobi Jr. was specifically designed to work well with children, it was surprising to learn that other age groups made no distinction between the robots in choosing an interaction distance. There were however substantially more observations of children interacting with Mobi Jr. compared to Mobi Sr., and of young adults and adults interacting with Mobi Sr., indicating a preference of the respective age groups

Table 3: Mean chosen distance in centimeters between subject and robot in different contexts. The 68.3% confidence interval (2 standard deviations) is shown in brackets. Significant results are underlined and bold.

	Child	Teenager	Young Adult	Adult	All Ages
Male	28.7 <15.5,53.0>	<u>39.9</u> < <u>23.7,67.0</u> >	57.1 <30.5,107.0>	<u>93.5</u> < <u>44.8,195.2</u> >	42.5 <20.6,88.0>
Female	33.3 <14.7,75.8>	<u>60.3</u> < <u>33.2,109.4</u> >	49.0 <33.7,71.4>	<u>232.9</u> < <u>176.6,307.1</u> >	53.6 <25.5,112.7>
Small Robot	<u>26.8</u> < <u>14.4,49.7</u> >	52.0 <29.5,95.0>	42.5 <42.5,42.5>	200.1 <117.1,342.4>	38.4 <16.9,87.2>
Big Robot	<u>70.4</u> < <u>36.7,135.1</u> >	55.1 <30.0,101.2>	53.8 <31.4,92.2>	91.4 <43.5,192.0>	58.4 <31.9,106.7>
All Groups	30.4 <15.1,61.1>	53.8 <29.5,98.0>	<u>47.6</u> < <u>20.3,111.6</u> >	126.7 <59.6,269.6>	47.9 <22.8,100.5>

for those robots. While robots can be created with a myriad of possible appearances, it appears that the look of the robot is more important in appealing to a certain target audience than it is in influencing the preferred interaction distance. In this way, the appearance might be modeled with practical considerations in mind, such as the placement of sensors and visual or auditory outputs, or it might be made to resemble the target audience members, leading to a smaller cultural difference.

Instead of simply applying a set of learned norms to the robots, it is possible that people actually used similar criteria of sensory input that are mentioned in Section 1.2. In this context it could mean that the distance is chosen to facilitate communication. Practically this would mean standing close enough to hear the operator’s voice through the speakers and to have the subject’s own voice be picked up by the microphone which can be determined by the operator’s communicated difficulty of hearing the subject. Mobi Sr. was shown at another exhibition where there was not enough light to see interaction partners through the webcam. A desk lamp was attached on top of its head, which influenced people’s decisions on where to stand since people tended to step into the light. Perhaps audio manipulations such as loudness or stereo placement will show a similar influence on communication distance.

The distribution of chosen distances has been shown to be logarithmically normal. Although not necessarily logarithmic, a positively skewed distribution has been predicted by Sundstrom & Altman [?], and has been found in another human-robot interaction study by Walters et al. [?]. This means that in an approach starting from afar, comfort builds up slowly to an optimum and then drops off rapidly, possibly due to the undesirability of physical contact. Practically this means that if in doubt, it is better for a robot to stay back a bit too far rather than coming a bit too close, since overshooting the optimal distance will cause a much greater discomfort.

The average interaction distance of 47.9 cm is close to the verbal interaction distance of 62 cm reported by Koay et al. Note that our value for young male adults is even closer to the verbal interaction distance reported by Koay et al. [?]. However, the variance observed in this study is much larger than the variance previously reported: the differences in measured distances observed for human-robot proxemics studies is typically of the order of less than 20 cm. This is partly due to the effect of children interacting at close distance with the small robot, and female adults observing the

robots from a far distance (note that these are independent observations, and is not explained by for example mothers watching their children interact). Yet, even for the Teenager and Young Adult groups, the variance was larger than previously reported, which is an indication of the variety of the audience attracted to this public event.

Surprisingly, the crowdedness of the environment is not significant in any of the groups. Having a surplus amount of space available to choose a position and communication distance was not expected to influence the choice, but given severe constraints people would still rather stand even closer to other people, than give up any space between themselves and the robot. There may be an alternative explanation however. Since the Mobi robots were a visitor attraction, people tended to crowd around them. This behavior led to spatial constraints for the people communicating with the robots at the front of the crowd. However, these subjects could have taken their preferred distance before the crowd limited them since people would gather behind or beside the subject not to disrupt his or her communication with the robot. Moreover, given the amount of space in the factory halls, there would typically be enough space around the crowd to provide everyone in it with at least personal distance. Investigating communication distance between humans and robots in truly crowded environments would be difficult because of navigational problems. Perhaps human-robot distance preferences in such crowded conditions can be determined in an elevator setting, where there is no need for the robot to navigate through a crowd if it is the last one to exit and the first one to enter the elevator.

Pacchierotti et al. [?] describe a learning effect where comfortable distance becomes closer depending on whether a subject interacted with their robot in a previous trial. This could simply be caused by familiarity, but it might also be caused by a higher predictability of the robot’s behavior which leads to a better estimate of whether or not the robot might be dangerous in any way. Apart from removing the need of keeping a cautionary distance, increased predictability and trust might also reduce the preferred interaction distance.

Additionally, a policy should be decided upon for dealing with learning effects. People may want to change their interaction with a certain robot or change their interaction distance as trust and familiarity is increased. To disregard initial cautious reactions on the human part would cause an unpleasant acquainting. On the other hand, to stay on the safe side and display solely more reserved manners might be

come a nuisance to frequent users. Ideally, robots should develop a social recognition system that determines whether or not any given person has been encountered before and what his or her attitude is towards the robot. However, such a system would normally not be available for all but the most advanced robots since the implementation of such a system is a far greater challenge than social distance maintenance.

7. CONCLUSIONS

It has been shown that age group is a significant factor in determining the preferred interaction distance, and furthermore that age group is of influence on what other factors play a role. Although the current work supports the notion that robot shape contributes mostly to appeal to a certain audience, it remains an open question if the shorter distances found in children's interaction with Mobi Jr. had practical grounds or were because of identification leading to a smaller cultural difference. Also, it remains unclear why there is a difference between the distance chosen by men and women in some age groups, whether or not this is related to cultural difference, and if the greater distance suggested for adult women is justified.

The influence of crowdedness and available space was not found to be significant in this work. Since the found preferred interaction distances were comparable to human personal and social space even when the environment provided enough capacity to keep public distance, there is no reason to doubt that any constraints that still provided the possibility to keep these distances were of any influence. In the case of intimate distance constraints however, the preferred distance would typically not be available without harming the preferred distance kept to other individuals. But in the current experiment, this space was available and the distance constraints were created only locally by crowding around the robot. Therefore, a further experiment is needed to establish the influence of severe spatial constraints in an environment that truly limits subjects to intimate distance.