October, 2007

Submitted for the degree of
Master of Cognitive Science

ROBOT PROXEMICS

TIM VAN OOSTERHOUT

Under supervision of Arnoud Visser
Graham Smith | Robbert Smit

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 are expected to follow similar rules. The current work tries to identify these rules in two contexts: in conversation-like interaction and in motion.

For the measurement of interaction distances a visual method is presented. 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.

To investigate social rules in motion, a system using simple direct wiring between two distance sensors and two motors was implemented and evaluated. It is argued that the employed method provides more natural social behaviour and is versatile despite its simplicity.

Contents

List of figures

List of tables

1 Introduction

Looking at science fiction, it appears that there is a great gap between the abilities that robots are given in the stories and reality. And even then, there remains a gap between what experimental robots can do and to what use robots are usually put in practice. On one end we have the notion of androids, or human-like robots, that walk on two legs and talk using natural language. These robots are very intelligent and most if not all aspects of interaction with them are humanlike and natural. On the other extreme, there are the majority of robots that are actually in service today. These are the industrial mechanical robot arms that weld, paint, assemble or are otherwise used in mass production. These robots typically do not show any intelligence and will not adapt to any unforeseen situations, making the physically strong models potentially dangerous if not operated properly.

It goes without saying that the industrial robot has no place in people's homes or in offices, or in any setting where they are likely to encounter people who were not trained to operate them. However, robotics has progressed far enough to allow gentler and smaller robots to be built. Robots have been made and brought to market that can do simple chores such as vacuum cleaning or mowing the lawn. Another use where robots have booked some success is entertainment, usually in the form of robot pets or companions. While it is still a long way to go before anything that resembles the science-fiction android can be realized, further advancements in artificial intelligence enable the creation of more intelligent robots that can perform a greater array of tasks, making it more realistic and possibly 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 adapt to a multitude of situations (all but the most technology alienated people can learn the daunting task of programming a VCR), if robots are to interact with people on a daily basis then they must 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 to identify some of the social rules that apply to human-robot interaction. Two contexts were chosen providing two very different views on what is essentially the same problem. To reflect this, the current work consists of two parts. In the first, the notion of proxemics is introduced as it is used in human sociology, and an attempt is made to apply it to human-robot conversation-like interaction. This part also introduces the robots that were used in both experiments. In the second part, a preliminary study is presented in which movement and behaviour is examined. Seemingly complex and purposeful behaviour can be achieved using very simple wiring. This technique is applied and evaluated in the context of social interaction.

2 Proxemics

2.1 Introduction

The field of proxemics is concerned with social distance, personal 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 social distance. Where the boundaries of these spheres exactly lie is determined by factors such as gender, relation or social distance, age and culture (Hall, 1966; Heshka & Nelson, 1972; Naidoo, 2000). 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.

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

Table 1: The four spheres of physical distance corresponding to social distance according to Hall

2.1.1 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 where interaction partners can cooperate to make physical contact (Hall, 1966).

At intimate distance, the interaction partner is so close that he or she may take up most of the vision area. In addition, body heat and smell may become noticeable. Verbal communication can be achieved at low levels or even at the level of whispers and other possibly involuntary sounds like breathing are audible. Finally, touching requires very little effort at this distance and may occur unannounced and unexpected.

At personal distance, the sense of body heat disappears, as does the sense of smell. There is now room to focus visually on the interaction partner and facial expressions, but on other things as well. The interaction partner is still within touching range, but touch can be predicted and is bound by social rules.

Social distance defines the upper range where normal one to one communication can occur. The only usable senses are hearing and vision, both of which may experience interference at this distance. From 2.4 m onwards, ongoing interactions are easily disengaged and other people may be ignored.

Finally, public distance requires special effort of the voice. The speaker may talk louder than normal or use aids such as a megaphone or a microphone. The whole body can be seen in a single glance and facial expressions are hard to discern or lost completely (Griffin, 2005).

2.1.2 Human-robot interaction

Although human-robot interaction has been studied, research in this area seems to focus on finding appropriate behaviour patterns (Pacchierotti, Christensen, & Jensfelt, 2006) or navigation (Althaus, Ishiguro, Kanda, Miyashita, & Christensen, 2004). In proxemics studies, the focus lies on human-human interaction, sometimes in virtual environments (Bailenson, Blascovich, Beall, & Loomis, 2003). 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 odour or body heat, sensory input can no longer explain or predict appropriate distances, even if the limitations on vision and hearing may still apply.

In the current research, human-robot interaction is assumed to take place in a personal or social zone equivalent. At present, robots are not delicate enough to make intimate interaction desirable. Robots could take the role of public speaker, but if they do, the interaction distance would be determined by external factors such as the location and density of the audience or the presence of a stage. As a consequence, choosing an appropriate distance would be trivial and would furthermore not have to be precise. 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. Below, 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 and a hypothetical prediction on the factor's influence based on the inclusion rationale. Factors that were not included were factors that are irrelevant for a robotic interaction partner, such as body heat or smell.

2.1.3 Included factors

- **Robot type**. 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. The experiment includes a smaller child-height robot that features slightly more round shapes, and a taller adult-height robot that features more prominent two-way communication through the use of a monitor mounted on the robot (see Materials). Based on these points, it is predicted that children will prefer to interact with and stand closer to the small robot, and adults will prefer the big robot.

- **Subject height**. 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 (Naidoo, 2000). This is one reason to include it in the current research, but there is another one. 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 (Working-Well, 2007). 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. Therefore, it is predicted that subjects who are the same height as the robot may stand closer, whereas subject whose height differs a lot from that of the robot (both taller and shorter subjects) may be forced to keep more distance proportional to the height difference.

- **Subject gender**. Since gender is an important factor in human proxemics (Heshka & Nelson, 1972; Naidoo, 2000), 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 Materials and Methods). The operator's gender was neither controlled nor kept track of. Any influence from the operator's gender is ignored since the measurements are pooled. Any influence found would then represent how men's and women's preference are different in regard to a genderless robot. Based on men's affinity for technology, it is predicted that men will prefer a shorter distance than women.

- **Subject age**. Age is a factor in human social distance and therefore in human proxemics (Hall, 1966), thus it might also be of influence in human-robot proxemics. The same complication with the operator's gender (see above) arises, and it is disregarded on the same grounds. What influence age would have in the current research was hard to predict, as it might be an indication of curiosity which may lead to shorter distances, or avoidance because of fear/unfamiliarity. Based on previous research (Baxter, 1970), it is predicted that children will stand closest, adolescents intermediate, and adults furthest.

- **Environmental crowdedness**. 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. For lack of a reason to think otherwise, it is predicted that subjects stand closer to the robot in a way that is comparable to the way they must stand closer to other human beings.

Factor	Predicted effect
Robot type	Children prefer a smaller robot
Subject height	Height difference causes greater distance
Subject gender	Men stand closer
Subject age	Younger subjects stand closer
Environmental crowdedness	Spatial constraints cause smaller distance

Table 2: summary of investigated factors and their predicted effects

2.2 Materials

Two robots were used in the current experiment (Figure 1). They could be controlled by volunteers through a desktop computer to which the robots were connected via a wireless network. Locations are referred to from the operator's point of view, local being the location of the operator/desktop computer, and remote being the robot's location.

2.2.1 Robot 1: Mobi Sr.

Figure 1: The two robots and the team that built them.

The first robot, called Mobi [1] Senior, 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 white with some black details and shaped functionally in the first place to house all the necessary equipment, and 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 also had a webcam allowing the operator to view the remote location. The remote webcam was mounted directly above the robot's monitor. In addition, the robot had stereo speakers and a microphone, and the operator's computer had a stereo headset and a microphone as well. These enabled two-way audio communication between the operator and an interaction partner at the remote location. The addition of two way video communication yielded a result very similar to a teleconference. Unlike a teleconference however, the operator could move the robot backwards or forwards and rotate it left or right around its axis by using the arrow keys on the local keyboard. Moreover, the interaction partner would not be in a typical desktop setup. Combined with the added mobility, this allowed the operator to establish a presence at the remote location through the robot that the interaction partner did not have to prepare for.

2.2.2 Robot 2: Mobi Jr.

A second, smaller robot was used called Mobi Junior. It had many of the same features as Mobi Senior, with the most notable exceptions of lacking a

[1] Mobile Operated Bi-directional Interface.

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° up and 25° down. Its shape was quite different, but featured the same black and white colour scheme. 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.

2.2.3 Control implementation

The robots were driven by Mac minis and used iSights as their webcams and microphones. At the operator’s end, an Apple eMac was used for each robot. To establish the videoconference iChat was used. Custom software was needed to facilitate the movement controls on the operator’s computer. This was implemented by having the Mac minis run a web server which hosted a flash application. The operator’s computer would display this application in a web browser. As a result of this, the operator’s computer could not display the video conference full screen as the robots did. The flash application showed four arrow keys as they are commonly laid out on a standard computer keyboard and communicated the movement key presses to the robot’s Mac mini, which would respond to these commands by sending out the appropriate signals to the custom hardware and motor controls through a USB serial port. At the time of data collection, no built in safety mechanisms prevented the operator from driving the robot into objects or people. However, an emergency stop signal could be issued through a radio remote control, which was operated by a Mobi team member who would be in the vicinity of the robot at all times.

2.3 Methods

2.3.1 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.

2.3.2 Procedure

To determine the appropriate social distance the robots would 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 Visual measurement). 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 showing as much as five. In total 72 photographs were used, depicting 106 subjects in 140 observations.

Because of the observational nature of the experiment, subjects were not approached by the researcher to fill out any questionnaires. Therefore, subject age and length had to be determined by other means. Subject length could be measured on the photograph (see Visual measurement) and subject age was estimated. Because of the imprecise nature of estimation, age was restricted to four categories shown in Table 3.

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

Table 3: Age categories used in the proxemics experiment

Environmental crowdedness was quantified with Hall's four spheres of personal distance in mind. Not all subjects were completely free in choosing an interaction distance. The crowdedness that subjects had to deal with could force them to stand closer than they would have done if they had a choice. A person limits the subject if the subject can not stand further away from the robot without running into this person. This occurs especially often if the blocking person already stands relatively close (within personal space of the robot) or if the environment is especially crowded, prohibiting the subject from standing beside the blocking person. The environmental crowdedness is determined as the biggest sphere in which the subject may choose to stand, even if the sphere is not entirely available. The actual distance the subject chooses can be classified at most as this sphere, or a smaller one.

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

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 it was clear that the pictured subject was not yet seen in the distance measuring photographs and that the interaction met the previously stated requirements. In total, 135 unique subjects were counted.

2.3.3 Measured distance

The exact measured distance is usually nose-to-nose distance (Willis, 1966; Baxter, 1970; Heshka & Nelson, 1972). 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[2] (pictured as an X in Figure 5). 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

[2] This point can be determined with the help of a baseline that connects the subject's feet.

stand over smaller objects. In the chosen scheme this fact can be expressed, which was necessary because subjects could stand over the smaller Mobi Jr.'s base. 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 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.

2.3.4 Visual measurement

Digital photographs were used to determine the actual distance to the robot chosen by the subject, subject height and the distance between the robot and the nearest blocking person to determine the environmental 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 (Heshka & Nelson, 1972). Since all the measurements from the robot were known, a ratio between pixels and centimetres could easily be established using any measurement that does not extend out of this plane such as robot height or the length of the robot's side. This ratio then related pictured lengths to actual lengths, with which subject

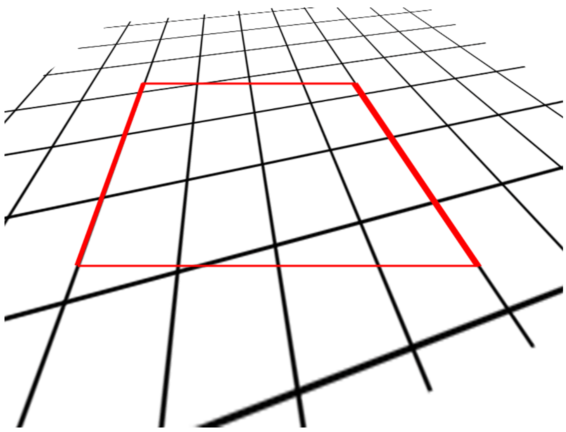

Figure 2: Parallel lines in perspective with a highlighted trapezoid constructed from a random pair of horizontal lines and the pictured perspective lines.

distance 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-centimetre precision for size measurements[3] and distance measurements without a perspective element.

In photographs where robot and subject were not in the same parallel plane, perspective distortion had to be corrected for. Determining the exact location of the camera (or photographer) relative to either the robot or subject might have facilitated the measuring procedure, but doing so would have disturbed the experiment and drawn too much attention to the researcher, just as measuring the distance between robot and subject directly would have. Because the camera position and angle were not recorded, 2D x- and y-coordinates from the photograph could not be mapped directly to 3D coordinates, even if these coordinates were restricted to the floor plane. Instead, another method was used utilizing two pairs of intersecting parallel lines.

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 thus to each other[4]. The two pairs will enclose a trapezoid in perspective projection (Figure 2). The ratio between the length of the top and bottom of the trapezoid, P_{r2} and P_{r1} respectively, both shown in figures 3, 4 and 5, provides the amount of decrease in size due to perspective distortion over a distance D_r 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 on any given position (height in the photograph) 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.

[3] The robots were 112 and 175 centimetres tall, see Materials.

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

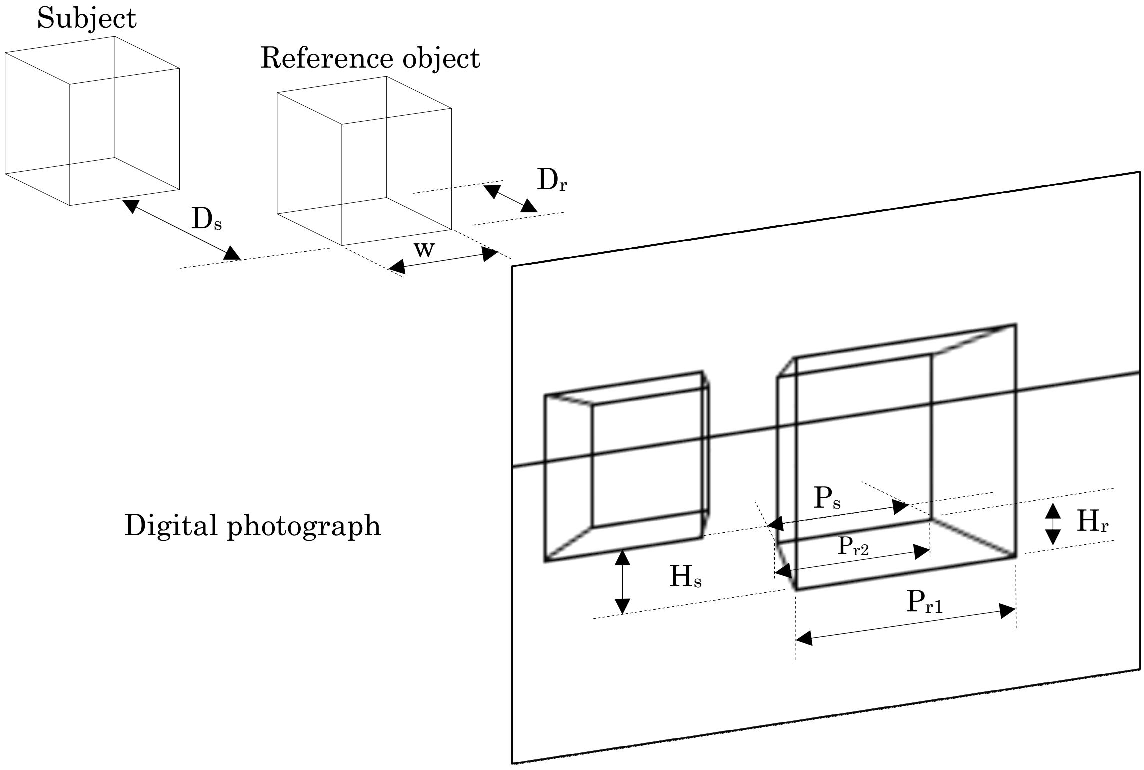

Figure 4: The reference object and the subject in the world and in a photograph.

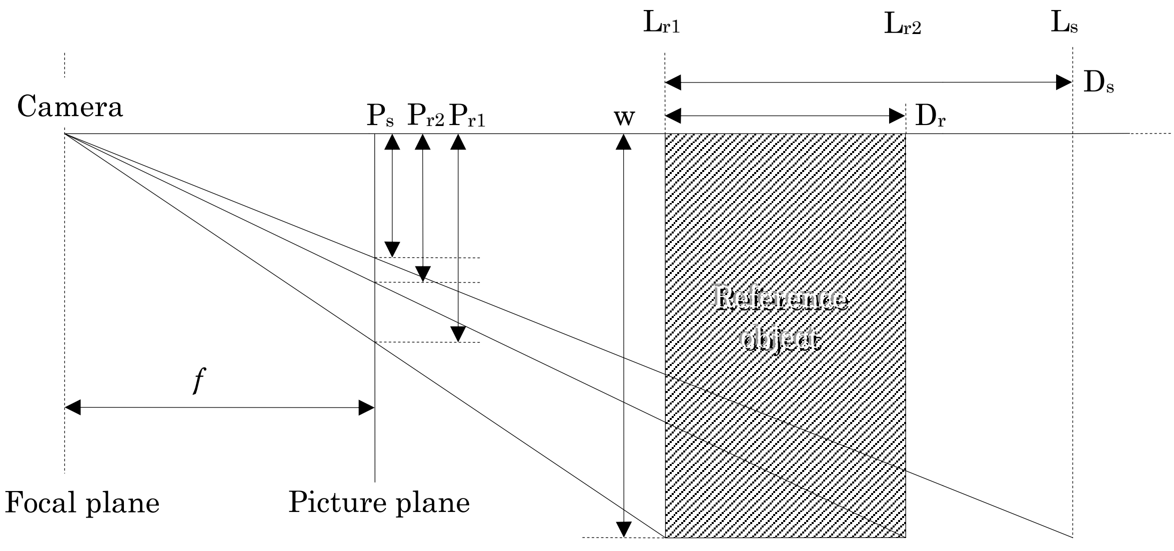

Figure 3: The reference object seen from above, lined up against the optical axis of the camera.

To obtain the distance between any two points on a plane, a different 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, and should therefore contain a distorted component and thus be not parallel to the focal plane. Let us assume for now that the depth reference D_r is in fact perpendicular to the focal plane. An unknown depth D_s can then be computed by expressing it as a ratio of the depth reference D_r.

To demonstrate this, let's express a depth distance between the focal plane and a random point. If the known width w of a reference object is available, then we can use any projection of this width on the picture plane (projections P_{r1}, P_{r2} or P_s) and the focal distance f to compute the distance from the focal plane to the location from which w was projected (locations L_{r1}, L_{r2} or L_s respectively) using similar triangles (see Figure 3). When expressed as a ratio of distances, the focal distance and reference measure w can be eliminated:

$$\frac{D_r}{D_s} = \frac{\frac{w}{P_{r2}}f - \frac{w}{P_{r1}}f}{\frac{w}{P_s}f - \frac{w}{P_{r1}}f} = \frac{\frac{1}{P_{r2}} - \frac{1}{P_{r1}}}{\frac{1}{P_s} - \frac{1}{P_{r1}}} = \frac{\frac{P_{r1}-P_{r2}}{P_{r2}P_{r1}}}{\frac{P_{r1}-P_s}{P_sP_{r1}}} = \frac{P_sP_{r1}(P_{r1}-P_{r2})}{P_{r2}P_{r1}(P_{r1}-P_s)} = \frac{P_sP_{r1}-P_{r2}P_s}{P_{r2}P_{r1}-P_{r2}P_s}$$

Equation 1: Expressing the ratio of two distances.

Where D_r is a known reference distance that represents the depth of the reference object, and 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. Since P_s must be calculated from P_{r1}, P_{r2} and the height differences H_r and H_s (see Figure 4), this step can be combined with Equation 1 by replacing P_s with the appropriate term:

$$P_s = (P_{r2} - P_{r1})\frac{H_s}{H_r} + P_{r1}$$

Equation 2: Calculating P_s.

and simplifying to the following form (see Appendix A):

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

Equation 3: calculating the ratio of distances without P_s.

Both distances D_s and D_r must be perpendicular to the focal plane. If the reference object is not aligned in a manner such that such a distance can be determined directly, 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. In a similar way, the actual distance on the floor between any two projected points (i.e. points on the photograph)

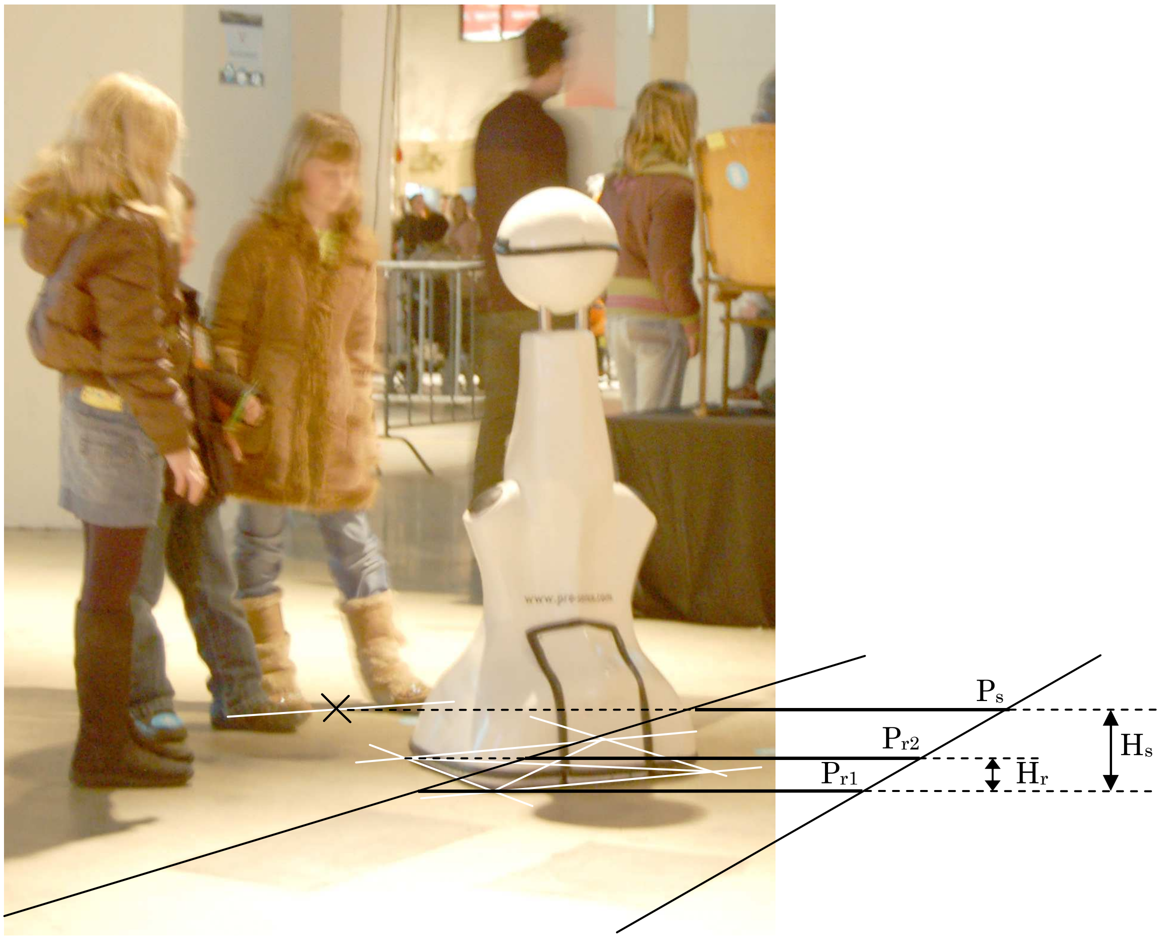

Figure 5: An example of measurements on an actual photograph (faces have been blurred).

can be calculated from a component perpendicular to the focal plane, and a component parallel to it. Reference depth measurements in the current experiment (H_r) ranged roughly from 60 pixels to 450 pixels to capture a length of typically around 55 cm, giving almost centimetre precision or better.

2.4 Results

140 Observations of 106 people were collected during a three day period. A Shapiro-Wilk test revealed that the 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 dataset had a mean of 3.87 which corresponds to a distance of 48 cm, and a standard deviation of 0.74. Subtracting or adding one standard deviation and transforming back to centimetres gives a distance of 23 cm and 100 cm respectively (Figure 6). The

absolute number of observations per condition is presented in Table 4 and Table 5.

Mobi Jr	Intimate m / f	Personal m / f	Social m / f	Public m / f	Total m / f	(tot)
Child	0 / 0	3 / 2	8 / 8	12 / 7	23 / 17	**(40)**
Teenager	0 / 3	1 / 1	0 / 1	8 / 6	9 / 11	**(20)**
Young Adult	0 / 0	0 / 0	0 / 0	1 / 0	1 / 0	**(1)**
Adult	0 / 0	0 / 0	0 / 2	3 / 0	3 / 2	**(5)**
Total	**0 / 3** **3**	**4 / 3** **7**	**8 / 11** **19**	**24 / 13** **37**	**36 / 30** **66**	

Table 4: number of observed interactions with Mobi Jr per condition. M/f denote male / female category, (tot) denotes total.

Mobi Sr	Intimate m / f	Personal m / f	Social m / f	Public m / f	Total m / f	(tot)
Child	0 / 0	2 / 0	2 / 1	1 / 0	5 / 1	**(6)**
Teenager	1 / 0	2 / 3	1 / 13	0 / 7	4 / 23	**(27)**
Young Adult	0 / 1	2 / 1	11 / 7	5 / 6	18 / 15	**(33)**
Adult	0 / 0	1 / 0	1 / 0	3 / 2	5 / 2	**(7)**
Total	**1 / 1** **1**	**7 / 4** **11**	**15 / 21** **36**	**9 / 15** **24**	32 / 41 **73**	

Table 5: number of observed interactions with Mobi Sr per condition. M/f denote male / female category, (tot) denotes total.

The natural logarithm of the chosen distance was analyzed using an analysis of variance with a 2×2×4×4, Robot type × Gender × Environment × Age group, unbalanced fractional factorial design. Since there were significant effects for Age group × Robot type [$F(3, 124) = 6.75$, $p < .0005$] and Age group × Gender [$F(3, 124) = 2.67$, $p = .05$], additional analyses were conducted per age group using a 2×2×4 design. In no case did the environment reach significance. For children, robot type was significant [$F(1, 41) = 12.12$, $p = .001$]. Gender was significant for teens [$F(1, 41) = 5.00$, $p = .03$] and marginally significant for adults [$F(1, 7) = 5.18$, $p = .057$]. Robot type and Gender were not significant in any of the other age groups.

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 7 shows the mean distance in centimetres for the significant groups. Since means and standard deviations were computed under logarithmic transformation, the distances these standard deviations represent are not equal in both directions. Therefore, the mean minus one standard deviation in centimetres is shown in subscript and the mean plus one standard deviation is shown in superscript.

Figure 7 shows the relative number of observations with each robot per age group. 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.

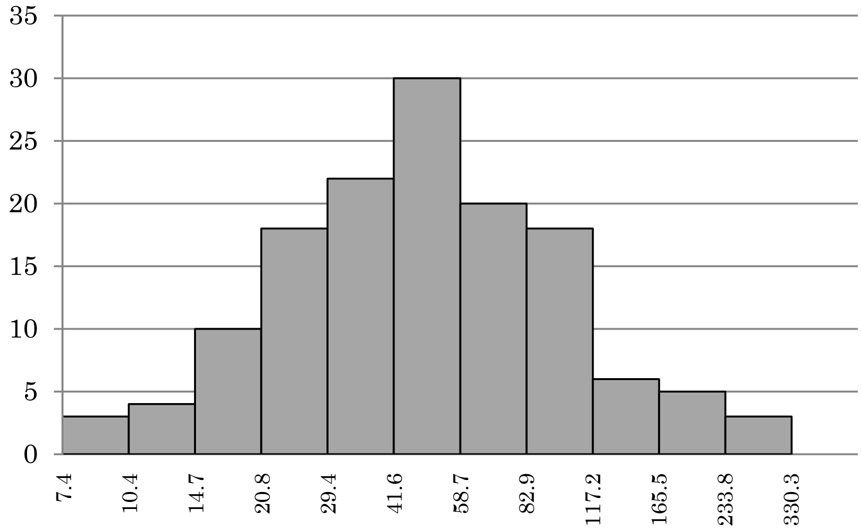

Figure 6: Observation counts per distance range in centimetres. Bin sizes increase logarithmically.

Factor	Effect found
Robot type	Significant for children.
Subject height	No effect found.
Subject gender	Only significant for teenagers and adults.
Subject age	Different effects per age group, no trend
Environmental crowdedness	No effect found.

Table 6: Predicted effect results

	Child	Teenager	Young Adult	Adult	All Ages
Male	28,7 $\{^{53,0}_{15,5}\}$	39,9 $\{^{67,0}_{23,7}\}$*	57,1 $\{^{107,0}_{30,5}\}$	93,5 $\{^{195,2}_{44,8}\}$*	**42,5** $\{^{88,0}_{20,6}\}$
Female	33,3 $\{^{75,8}_{14,7}\}$	60,3 $\{^{109,4}_{33,2}\}$*	49,0 $\{^{71,4}_{33,7}\}$	232,9 $\{^{307,1}_{176,6}\}$*	**232,9** $\{^{307,1}_{176,6}\}$
Small Robot	26,8 $\{^{49,7}_{14,4}\}$*	52,0 $\{^{95,0}_{28,5}\}$	42,5 $\{^{42,5}_{42,5}\}$	200,1 $\{^{342,4}_{117,0}\}$	**38,4** $\{^{87,2}_{16,9}\}$
Big Robot	70,4 $\{^{135,1}_{36,7}\}$*	55,1 $\{^{101,2}_{30,0}\}$	53,8 $\{^{92,0}_{31,4}\}$	91,4 $\{^{192,0}_{43,5}\}$	**58,4** $\{^{106,7}_{31,9}\}$
All Groups	**30,4** $\{^{61,1}_{15,1}\}$	**53,8** $\{^{98,0}_{29,5}\}$	**47,6** $\{^{111,6}_{20,3}\}$*	**126,7** $\{^{269,2}_{59,6}\}$	**47,9** $\{^{100,5}_{22,8}\}$

Table 7: Mean chosen distance in centimetres between subject and robot in different contexts. The 68.3% confidence interval (2 standard deviations) is shown in braces. Significant results are highlighted and marked with an asterisk.

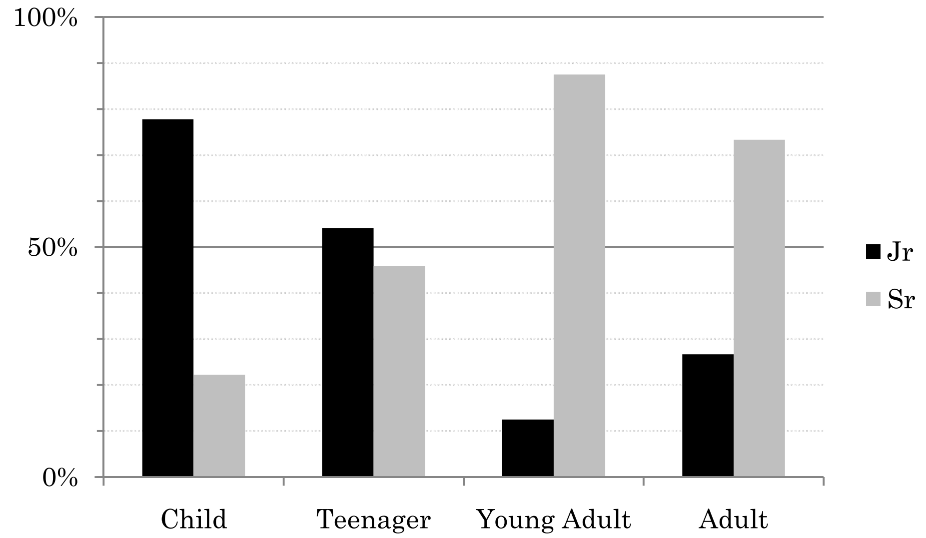

Figure 7: Observed interaction frequencies relative to robot type.

2.5 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 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 modelled 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 social distance.

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 2.1.1. 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. To overcome this obstacle, a desk lamp was attached on top of its head. A small square area showed the remote video feed to the subject so they could see themselves. Although no measurements were made at this event, it seems people came closer than they would have in normal lighting conditions, and it was clear that the light 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 (1976), and has been found in another human-robot interaction study by Walters et al. (2005). 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.

Surprisingly, the crowdedness of the environment is not significant in any of the groups. This is strange, since the robot is given the same amount of space, even when space is limited so much that people are forced to stand closer together. 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, albeit by only a small amount, 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 behaviour 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. Situations where subjects have only intimate space available may thus be caused artificially and by choice of the subjects instead of by necessity due to crowdedness or lack of space. 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.

3 Navigation

3.1 Introduction

Previous studies have argued that robots that exhibit social behaviour are considered safe and comfortable (Pacchierotti, Christensen, & Jensfelt, 2006). Moreover, it has been suggested that the robot would seem more sociable (Althaus, Ishiguro, Kanda, Miyashita, & Christensen, 2004) and even more intelligent than robots that do not exhibit social behaviour (Kanda, Ishiguro, Imai, Ono, & Mase, 2002). Since the previously reported distances apply to stationary interaction only, the Mobi robots were equipped with two sonars each to make them appear more social when moving. The sonars were wired like Braitenberg's vehicle 3b, which he calls an Explorer (Braitenberg, 1984). Such a vehicle has crossed inhibitory connections going from the sensors to the wheels. In the current study, the left sonar inhibited the right wheel with a force proportional to the closeness of the nearest object and vice versa (see Figure 8). The purpose of this addition was to keep the robots out of the intimate sphere of people while in motion. However, since the robots were still remote controlled, the Explorer wiring only applied when the operator provided a driving force forward. Turning on the spot was always allowed since there was minimal risk of hitting obstacles or people. The sonars were meant to aid the operator in steering clear of people and obstacles.

3.2 Implementation

The sonars were mounted 38 cm apart facing forward at a height of 63 cm, and had a beam width of 100° each. Two thresholds were defined: a turning threshold and a stopping threshold. When either sonar read a distance smaller than the stopping threshold, the robot would turn on the spot if the other sonar would still be above it. If both sonars read distances below the stopping threshold then the robot would stop. The operator would not be able to go forward again until the object or person disappeared or moved back, or until the operator would turn the robot on the spot so that either sonar or both gathered readings bigger than the stopping threshold. No distinction was made between objects or people. Given the different motor capabilities of the two robots, Braitenberg's Explorer wiring was implemented differently for each robot and both implementations used the turning threshold in a different way providing similar but different behaviours described below.

3.2.1 Mobi Jr.

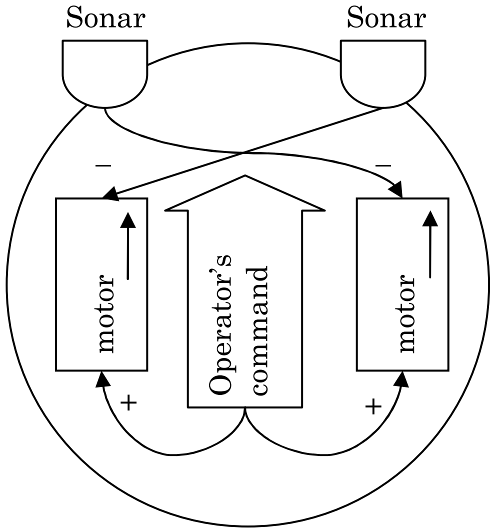

Figure 8: Braitenberg wiring schema

Mobi Jr.'s motors could only go forward, backward or stop. If one motor would go forward while the other went backward, the robot would rotate on the spot. If only one motor went forward, the robot would turn around the other wheel, effectively going forward while turning. If both motors went forward then the robot would travel at a speed of 0.45 m/s. In order to prevent the robot from entering people's intimate circle, the stopping threshold was set at 45 cm. The turning threshold was set at 55 cm, at which point the robot would initiate the forward turning movement. This distance was chosen so that the robot had enough manoeuvring distance to stay outside of stopping distance while executing the forward turning movement until the robot was allowed to go straight forward again. After the robot had avoided the obstacle or person, the operator could turn the robot to resume the previous heading if desired. It was possible however to come too close to a person coming towards Mobi Jr. or to encounter new obstacles or people while forward-turning which could result in a full stop. Because of the lack of acceleration, transitions between different movement types were sudden.

3.2.2 Mobi Sr.

Mobi Sr. was equipped with motors that could vary speed and acceleration. It would turn on the spot when both motors were activated at the same speed but in opposite directions. It had a top speed of about 1.25 m/s. Since Mobi Sr.'s motors were not discrete, a more elegant implementation could be made for it, which was also more true to Braitenberg's description. The turning threshold now represented a maximum distance at which to start reacting to sonar readings. The inhibitory force would then be applied such that the speed of the corresponding wheel would be zero at the stopping threshold and maximum beyond the turning threshold, and scaled linearly in between. The turning and stopping thresholds were empirically set at 100 cm and 20 cm respectively. This meant that Mobi Sr. could enter the intimate circle of a person, but because of the Explorer behaviour it would almost never do so and steer away rather than towards a person. If the operator wanted to actually come within 20 cm of a person, he or she would have to counteradjust the Explorer behaviour and even then Mobi Sr. would only approach at a crawl. Unlike Mobi Jr., Mobi Sr. did not have to switch between manoeuvres and followed the Explorer behaviour constantly when directed forward without sudden changes, except when the Explorer behaviour called for a sudden deceleration to avoid someone or something.

3.3 Evaluation

3.3.1 Setup

Both robots were tested and evaluated at the college premises where the Mobi robots were built. The locations included a room in a workshop setup with large tables, cabinets and other obstacles, and the adjacent hallway. The robots would be operated by Mobi team members. Subjects were students or occasionally professors who ran into random encounters with either robot as the team members were testing them. About 12 subjects were asked to comment on the robot and its behaviour in casual conversation by a team member other than the operator or by the operator in person after the encounter.

In addition, Mobi Sr. was set up at a social event for the Ministry of Education, Culture and Science. The event was held in a music venue, in which square tables and bar stools were placed. If all stools were occupied with no people standing in between, there would be just enough room for Mobi Sr. to get around in the table area. There was a stage on one end of the room with steps leading up to it. On the opposite side there was a buffet and there were bars on the flanks. Around the table area there were margins of about 2.5 m to the bars, 2 m to the stage but only 0.5 m where the steps were, and about 6 m to the buffet. The robot could get around the room through these areas if its passage was blocked in the table area due to crowding. Volunteers were encouraged to take control, with a team member filling in if there were no volunteers. As in the college setting, about 20 subjects were asked to comment on the robot and its behaviour by a team member other than the operator.

3.3.2 Results

Because Mobi Jr. could only exhibit three motion patterns when in motion (forward, forward-turn, turn on the spot) with sudden transitions between them, its behaviour was seen as mechanical. Because of its small size and relatively slow speed, subjects had no fear that it would injure them, although subjects were inclined to step out of its way when it approached them directly. Subjects who did not were pleased to see it turn away and pass them, having expected it to hit them in some cases. Subjects who did step aside initially would typically test its avoiding behaviour if the robot came towards them a second time after having seen its avoiding behaviour. All subjects were confident that Mobi Jr. would not hit them after they had seen it wander about and avoid some obstacles, walls or themselves. Subjects ascribed some intentionality to the robot, saying that it “tries” to follow the wall or go around obstacles etcetera, or that it “does not want” to collide. Some subjects challenged the robot’s ability to avoid them by purposefully blocking it, getting in its way again after it turned away or guiding it to corners or dead ends, and would sometimes “feel sorry for him/it” or said they were “teasing him/it”.

Mobi Sr.’s behaviour was much more consistent because of the lack of switching between manoeuvres. It was described as “quite natural” and by subjects who had seen both robots as “more elegant than Mobi Jr.” Subjects had some concerns that Mobi Sr. might be able to injure them because of its size and estimated weight. Its relative fast top speed would also make it harder to avoid. Most subjects from the college setting stepped out of the way if it came towards them. Here too they would test the robot if it came at them a second time after they had seen its avoidance behaviour. The slowing down when it approached was seen as reassuring and seemed to earn their trust that it would not injure them. Since Mobi Sr. would be travelling at slow speeds nearly all the time in the social event setting due to crowding and the large amount of obstacles (tables and stools), no one stepped out of its way out of concern for being hit, although people would give way to let it pass. Comments about “wanting” and “trying” were heard similar to those made about Mobi Jr. Additionally, subjects described Mobi Sr. as “careful” in both settings. When trying to pass a door, Mobi Sr. necessarily came close to the doorway and would move slowly before successfully aligning with the doorway, after which the robot would pass the door and accelerate when the doorposts were no longer being picked up by the sonars. This behaviour has been described as the robot being “afraid to pass the door”.

3.4 Discussion

People’s tendency to anthropomorphize was seen for both robots. However, in the case of Mobi Jr., its mechanical movements hindered this effect, as did situations where the stopping threshold was reached and the robot was no longer allowed to move until the operator reacted. As the robots justified anthropomorphizing them by displays of successful manoeuvring, subjects’ trust for and comfort around the robots seemed to increase, possibly strengthening the effect and encouraging attribution of more human traits to the robots than they actually possessed.

Hall determined a set of factors that according to him make up the human perception of space, and visualised the range of each of them (Hall, 1966). All of his factors' strengths either increase or decrease monotonically over distance, although some of these factors do not change linearly over distance. Given that there exists a preferred interaction distance, it follows that there are combined preferred observed strengths for these factors. This can mean that at the preferred interaction distance the factors that would make one want to approach are exactly countered by the factors that make one want to back up. Alternatively, it can mean that Hall's factors are non-linear and do not exclusively repel or attract, but can do either depending on its observed strength. The repulsive force in the current navigation experiment was linear, in following the most basic implementation of a Braitenberg vehicle. But Braitenberg himself talks about mapping sensory input to motor output using different functions (Braitenberg, 1984). The robot could signal the fact that it senses a person by reducing its speed, but not start its avoiding behaviour until when it comes even closer. The distance at which it steers away and by what amount, and the speeds it maintains during each phase of the avoidance procedure can all be fine-tuned. In addition, many different behaviours can be achieved just by changing the response to proximity levels. For example, the behaviour could be set to avoid people, follow a person, or approach a single person. With more distance sensors the robot could take a place in a circle of people or adjust the distance at which to avoid a person depending on available space. More advanced sensing could take the speed of the other person into account or react differently to people and objects. With the proper research on what are important factors and what are appropriate settings, all of these measures could increase the level of trust and comfort experienced by both interaction partners and bystanders.

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 (Pacchierotti, Christensen, & Jensfelt, 2006). A similar effect has been observed in the current experiment, where people trusted the robots more depending on their having seen the robot interact with its environment and even more if the subjects had interacted with the robots themselves. This could simply be caused by familiarity, but it might also be caused by a higher predictability of the robot's behaviour which leads to a better estimate of whether or not the robot might cause injury or be dangerous in any other way. The latter seems more likely, since anyone would wisely keep their distance from a blind flame throwing robot, no matter how familiar one is with it. Apart from removing the need of keeping a cautionary distance, increased predictability and trust might also reduce the preferred interaction distance or influence the distance to the robot at which people still feel comfortable.

Behaviour is an important way of signalling intention. For instance, it is usually clear if an oncoming person is going to pass you by or approach you to ask a question or engage in some other interaction. Since people tended to step out of the way, the current navigational behaviour would obviously not be a suitable one if applied to approach people to engage interaction. Possibly the approach speed remained too high for this goal, or the robot started slowing down too late for the subject to realize that he or she had in fact been detected by the robot. Especially in the case of Mobi Jr., it may simply be unclear what the robot's (or operator's) intentions are, making it difficult to decide how to react to a certain movement. Combined with learning effects, familiarity could help in deciphering the robot's intentions and any suboptimal behaviour could still achieve success. However, as stated in the introduction, it is desirable to achieve such behaviour that people unfamiliar with a particular robot can still successfully and comfortably interact with it.

4 Summary and general discussion

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 social distance, or perhaps because of still other reasons. 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 social distance, 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.

Other environmental features than crowdedness and available space might influence interaction distance. A spotlight has already been identified as one such influence, although its parameters (wideness, brightness, colour, focal point) have not been investigated. An interesting question would be if people would still stand in the spotlight if it would make them stand further back than they would have, even until audio communication becomes problematic. Also, a spotlight might identify a region that people would want to stay out of while the robot navigates. Apart from light, other visibility issues such as fog might influence not only interaction distance, but might also impact experienced comfort if the robot navigates at normal speed with sensors that are not hindered by the reduced visibility. Another influence might be background noise, especially in combination with the robot's audio loudness.

The logarithmic distribution of distances found in the proxemics experiment might provide a basis for the mapping function of measured distances to motor inhibition. The logarithmically transformed standard curve could provide the desired inhibitory force such that the speed is reduced to zero at the optimal distance. At distances beyond this point, the direction of acceleration should be inverted to prevent the robot from speeding up again. Approaching the optimal distance from afar, this function would reduce the desired speed, easing to a stop, and cause the robot to back up when the optimal distance is overshot. A distinction should be made between approach behaviour and interaction distance maintenance though, since the robot should not necessarily back up if the interaction partner voluntarily comes closer, especially if the interaction partner only steps forward momentarily for example to let someone pass.

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 become 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.

Bibliography

Althaus, P., Ishiguro, H., Kanda, T., Miyashita, T., & Christensen, H. I. (2004). Navigation for Human-Robot Interaction Tasks. *Proceedings of the 2004 IEEE International Conderence on Robotics & Automation.* New Orleans.

Bailenson, J. N., Blascovich, J., Beall, A. C., & Loomis, J. M. (2003). Interpersonal Distance in Immersive Virtual Environmets. *Personality and Social Psychology Bulletin , 29*, pp. 1-15.

Baxter, J. C. (1970). Interpersonal Spacing in Natural Settings. *Sociometry , 33* (4), 444-456.

Braitenberg, V. (1984). *Vehicles: Experiments in Synthetic Psychology.* Cambridge, Massachusetts: MIT Press.

Griffin, E. (2005). *A First Look at Communication Theory.* Chicago: The McGraw-Hill Companies.

Hall, E. T. (1966). *The Hidden Dimension.* New York: Anchor Books.

Heshka, S., & Nelson, Y. (1972). Interpersonal Speaking Distance as a Function of Age, Sex, and Relationship. *Sociometry , 35* (4), 491-498.

Kanda, T., Ishiguro, H., Imai, M., Ono, T., & Mase, K. (2002). A constructive approach for developing interactive humanoid robots. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, (pp. 1265-1270). Lausanne.

Naidoo, S. (2000, Fall). *Gender, Ethnicity, Intimacy and Proxemics.* Retrieved August 7, 2007, from Penn Language Center: http://ccat.sas.upenn.edu/plc/communication/shivana.htm

Pacchierotti, E., Christensen, H. I., & Jensfelt, P. (2006). Evaluation of passing distance for social robots. *IEEE Workshop on Robot and Human Interactive Communication (ROMAN).* Hartfordshire.

Sundstrom, E., & Altman, I. (1976). Interpersonal Relationships and Personal Space: Research Review and Theoretival Model. *Human Ecology , 4* (1), 47-67.

Walters, M. L., Dautenhahn, K., te Boekhorst, R., Koay, K. L., Kaouri, C., Woods, S., et al. (2005). The Influence of Subects' Personality Traits on Personal Spatial Zones in a Human-Robot Interaction Experiment.

Proceedings of the 14th IEEE International Workshop on Robot and Human Interactive Communication, (pp. 347-352). Nashville.

Willis, F. N. (1966). Initial speaking distance as a function of the speakers' relationship. *Psychonomic Science , 5*, 221-222.

Working-Well. (2007). *Workstation Design*. Retrieved August 31, 2007, from Working Well Ergonomics Information Website: http://www.working-well.org/wkstn_design.html

Appendix A: Simplification of distance ratio

P_s can be determined by taking the amount that the reference measurement w diminishes over a height difference of H_r and scaling it to the height difference H_s (see Figure 4). Combining Equation 2 with Equation 1 gives:

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

$$= \frac{(P_{r1} - P_{r2})(P_{r2} - P_{r1})\frac{H_s}{H_r} + P_{r1}(P_{r1} - P_{r2})}{-P_{r2}(P_{r2} - P_{r1})\frac{H_s}{H_r}}$$

$$= \frac{(P_{r1} - P_{r2})(P_{r2} - P_{r1})\frac{H_s}{H_r} + P_{r1}(P_{r1} - P_{r2})}{P_{r2}(P_{r1} - P_{r2})\frac{H_s}{H_r}} = \frac{(P_{r2} - P_{r1})\frac{H_s}{H_r} + P_{r1}}{P_{r2}\frac{H_s}{H_r}}$$

$$= \frac{P_{r2} - P_{r1} + P_{r1}\frac{H_r}{H_s}}{P_{r2}} = \frac{\left(\frac{H_r}{H_s} - 1\right)P_{r1} + P_{r2}}{P_{r2}} = \left(\frac{H_r}{H_s} - 1\right)\frac{P_{r1}}{P_{r2}} + 1 \blacksquare$$

Equation 4: Extension of P_s and simplification.

Appendix B: Events where the Mobi robots were showcased

Date	Location	Occasion
March 23rd-26th 2006	Eindhoven	Arts and technology festival "STRP"
June 21st 2006	"De Waag" Amsterdam	Jubilee of the Waag Society
February 13th 2007	"t Paard van Troje" Den Haag	Ministry of Culture social event
April 10th 2007	Rotterdam	Arts and technology exposition