M. Lauckner, F. Kobiela, Dietrich Manzey

‘Hey robot, please step back!’ - exploration of a spatial threshold of comfort for human-mechanoid spatial interaction in a hallway scenario

Subtitle

Conference paper | Accepted manuscript (Postprint)
This version is available at https://doi.org/10.14279/depositonce-10990

Lauckner, M., Kobiela, F., & Manzey, D. (2014, August). ‘Hey robot, please step back!’ - exploration of a spatial threshold of comfort for human-mechanoid spatial interaction in a hallway scenario. The 23rd IEEE International Symposium on Robot and Human Interactive Communication. 2014 RO-MAN: The 23rd IEEE International Symposium on Robot and Human Interactive Communication. https://doi.org/10.1109/roman.2014.6926348

‘Hey Robot, please step back!’ – Exploration of a spatial threshold of comfort for Human-Mechanoid Spatial Interaction in a hallway scenario*

M. Lauckner, F. Kobiela, D. Manzey

***Abstract*— Within the scope of the current research the goal was to develop an autonomous transport assistant for hospitals. As a sort of social robots, they need to fulfill two main requirements with respect to their interactive behavior with humans: (1) a high level of safety and (2) a behavior that is perceived as socially proper. One important element includes the characteristics of movement. However, state-of-the-art hospital robots rather focus on safe but not smart maneuvering. Vital motion parameters in human everyday environment are personal space and velocity. The relevance of these parameters has also been reported in existing human-robot interaction research. However, to date, no minimal accepted frontal and lateral distances for human-mechanoid proxemics have been explored. The present work attempts to gain insights into a potential threshold of comfort and additionally, aims to explore a potential interaction of this threshold and the mechanoid's velocity. Therefore, a user study putting the users in control of the mechanoid was conducted in a laboratory hallway-like setting. Findings align with previously reported personal space zones in human-robot interaction research. Minimal accepted frontal and lateral distances were obtained. Furthermore, insights into a potential categorization of the lateral personal space area around a human are discussed for human-robot interaction.**

I. Introduction

New generations of robotic systems are gradually entering modern social environments to perform multiple services (e.g. transport, monitoring or teaching tasks among many others). These robots are in general referred to as service robots and need to interact with people as part of their normal operation. Therefore, they can be categorized as social robots. With respect to [1] a social robot is defined as “[…] a robot that makes itself ‘useful’, i.e. is able to carry out a variety of tasks in order to assist humans and behaves socially, i.e. possesses social skills in order to be able to interact with people in a socially acceptable manner.” According to further definitions regarding social robots it is of particular interest that a significant number of researchers claim for social robots the necessity of following the behavioral norms expected by the people [2]. The idea of the current research project aims at developing a ‘social service robot’ supporting hospital staff by autonomously transporting small goods of various kinds. A hospital confronts an autonomous system with a very heterogeneous social working environment (expert and non-expert users), leading to new challenges in the domain of HRI [3]. The human comfort regarding this type of robotic application will be essentially determined by the robot's physical design, its general behavior in a social environment and its specific behavior towards humans [2],[4]. Predictable robot motion behavior helps to facilitate interactions, to avoid annoying or even scaring people and contributes to a socially accepted robot companion [2],[5]. Humans do not walk around randomly in their environment, instead, motion carries social meaning. Correspondingly, the social capabilities of a robot should also comprise such non-verbal behavior like motion [6]. To date, several evaluations have revealed that the behavior of state-of-the-art service robots used in hospitals does not always meet people's expectations [7]. Furthermore, it can be stated that current systems rather focus on safe but not smart maneuvering [7],[8].

II. Related Work

One of the vital considerations for the design of a social robot's motion behavior is the idea of personal space [5]. It plays an important role in human-human interaction (HHI) and is defined by Sommer (p.26) as “an area with invisible boundaries surrounding a person's body into which intruders may not come” [9]. Edward T. Hall, pioneer in this field, has widely studied this phenomenon and established a notation system [10],[11]. Within this system Hall [11] identified four personal space zones for non-contact cultures (Northern European, Western European cultures, Caucasian American societies*)*: The intimate zone (ranging from 0 to 045m), the personal zone (ranging from 0.45m to 1.2m), the social zone (ranging from 1.2m to 3.6m) and lastly, the public zone (beginning from 3.6m). He based this categorization on visual estimations in terms of arm lengths. During several experiments with one of his colleagues he associated changes in voice with changes in distance [10]. Furthermore, each zone is reserved for certain relationships among people, e.g. the intimate zone for lovers, family members or close friends, the personal zone for conversations with friends or for waiting in line, the social zone for conversation with non-friends (e.g. business contacts) and the public zone for long range interaction like a speech or a concert [11]. In the following decades other researchers have devoted themselves to this topic, gathering more insights into human-human proxemics [12],[13]. Chosen and maintained interpersonal distances by humans depend on a huge variety of influencing factors: the existing relationship between the spatially interacting humans, age, gender, personality, cultural background, and social role, just to name some quite prominent ones among others

*Research supported by Robert Bosch GmbH.

M. Lauckner is with the Robert Bosch GmbH and doctoral student at Technical University Berlin, Germany
(e-mail: mathis.lauckner@de.bosch.com).
F. Kobiela is a senior researcher with Robert Bosch GmbH, Germany
(e-mail: fanny.kobiela@de.bosch.com).
D. Manzey is professor for Work, Engineering and Organisational Psychology at Technical University Berlin, Germany
(e-mail: Dietrich.manzey@tu-berlin.de).

[5],[9],[10],[12],[14]. Nonetheless, Stratton and his colleagues postulated a typical mean “comfortable” approach distance between humans of approximately 0.51m [13]. Furthermore, it is noteworthy to mention that the personal space zones relate to different distances around a human body [9]. It is assumed that they can be modeled as an ellipse around a person, being larger in front of a human compared to the lateral and back areas [15],[16],[17]. To sum up, it is crucial to know that a violation of personal space causes discomfort and is thus, a highly important aspect of human interaction [18].

With respect to HRI and a social robot’s motion behavior, personal space should be taken into account and seen as one of the primary social conventions those types of robots should respect when operating in a human environment [8]. Commonly applied terms for the personal space in human-robot interaction (HRI) are human-robot proxemics (HRP) or human-robot spatial interaction (HRSI). HRP ‘…studies how humans and robots use and manipulate distances between each other with regard to social behavior and human perceptions.’ [19]. HRSI is defined as ‘…a set of relative motion events between two or more agents, which are executed according to particular social rules, agents’ objectives, safety constraints.’ [20].

Due to the fact that the robotic prototype in the present study is a mechanoid, the field of research can be precisely called human-mechanoid proxemics (HMP). A Mechanoid is a robot which is relatively machine-like in its appearance, respectively, does not have any overtly human-like features [21]. Consequently, it is physically unable to move in ways that people do (non-holonomic) [8]. Despite the apparent importance of HRP, very little research has been conducted in this field [22].

In addition, a lot of studies are designed and conducted in an ad-hoc manner and not derived from theory [23]. Most research has shown that robots should stay outside of people’s intimate zone and rather within their personal or social zone [24]. In [5], Walters came up with an average grand mean of 0.57m regarding frontal distances in HRI across six conducted experiments. Unfortunately, his elaborated proxemic framework consists of many incomparable studies (e.g. with respect to distance measurement techniques, sample design and experimental setting) and therefore this postulated value remains to be further investigated. By comparing two specific HRP studies with each other it becomes quite obvious that the existing body of research still consists of heterogeneous findings: Walters et al. investigated comfortable human to robot and robot to human approach distances using a mechanoid - the PeopleBot [25]. Obtained mean distances were 0.71m for human to robot approach, and 0.88m for robot to human. Floor markings on the ground and a subsequent video analysis were used to measure the subjects’ chosen distances. The authors indicated a measurement accuracy of approximately 0.125m and subjects were instructed to either approach the robot to a comfortable distance or to say stop when the robot reached a desired distance. It is noteworthy that the robot to human approach distance was limited at 0.5m due to safety constraints of the PeopleBot. However, the authors reported that approximately 40% of all participants approached the robot up to or closer than 0.5m and that approximately 40% also let the robot come right up to this 0.5m limit. In contrast, in [26], Huettenrauch et al. found in another HRP study using the same PeopleBot that only a small minority of the subjects (approximately 10%) operated with the robot within their intimate zone. A striking majority of the subjects (approximately 75%) maintained distances towards the robot during the experiment that belong to the personal zone. These heterogeneous findings might have occurred due to different distance measurement techniques. Especially in [5] a measurement accuracy of 0.125m might not be sufficiently precise regarding human-robot proxemics. Moreover, a robot to human approach distance limit of 0.5m does not enable an exploration of the intimate zone. However, with respect to the two outlined research projects, it remains inconclusive in which personal space zone a potential threshold of comfort should be set. In a further study, researchers attempted to explore the personal space during an avoidance maneuver of a PeopleBot in a hallway scenario [6]. Even though only 4 subjects participated in this pilot study it provided some further insights into HRP. The robot’s speed, its signaling distance and its maintained lateral distance to the subjects were varied. After each trial subjects had to assess the experienced behavior in terms of comfort in a questionnaire. Larger distances were preferred, rather indicating support that the personal zone is preferred by people in HRP.

In general, considering a further relevant parameter of motion behavior, robot’s velocity comes up [27]. This motion parameter was explored by [6] as well. A velocity of 0.4m/s received better ratings compared to slower speeds. However, no faster velocities were tested. Again, as with personal space, an initial look at HHI provides insights into normal human motion behavior in terms of walking speed. According to Morgenroth [28], who observed human walking speed in several German cities, the average walking speed of a human is within a range of 1 to 2m/s. The velocity of a robot operating in human environment can lead to diverse evocations of feelings. A too fast robot might be perceived as aggressive or nervous [29], whereas a robot with really slow movements can be easily perceived as disturbing [30]. Despite these assumptions current research lacks a sufficient amount of studies identifying an ‘appropriate’ speed range for social robots in general. Empirical investigations concerning robot speed have shown that a velocity of 1m/s seems to be too fast for human comfort [31]. In general it is claimed that humans rather prefer a slower robot velocity compared to human walking speed [31]. However, the study of [31] lacks a sufficient experimental variation of speed. By only comparing 0.25m/s and 1.0m/s a wide range of velocities has not yet been a subject of investigation. In line with [31] a further study by Sardar and his colleagues [32] revealed a less comfortable assessment of 1.0m/s compared to 0.4m/s. However, the values between 0.4 and 1.0m/s were not investigated. Compared to human walking speed 0.4m/s is considered by the authors as still pretty slow and therefore it can be assumed to find an ‘optimal-like’ speed range between 0.4m/s and 1.0m/s. Furthermore, a wide range of research has obtained empirical evidence concerning an interaction of velocity and personal space. Already in 1995, Branzell and Kim [33] assumed the personal space bubble is increased by a faster velocity. This is also assumed by other researchers [12],[34].

In [35], Mizoguchi et al. explored several approaching velocities and found that the accepted approach distance increased with faster approach velocities of the robot. Unfortunately, no exact speed values were reported.

In summary, despite many shortcomings of existing HRP research, in general there is empirical evidence supporting the relevance of personal space and robots' velocity in HRI. However, no assumptions have been postulated regarding existing spatial boundaries in the current research, especially anything regarding the lateral areas of personal space [24]. Despite the crucial requirement not to violate the personal space of a human, a minimum distance value has not been explored for an approaching or passing mechanoid in a hallway scenario yet. Lastly, the existing body of research has elaborated empirical indications for a potential interaction of velocity and personal space.

Therefore, the main research question for the present study is the exploration of a minimum threshold of comfort for frontal as well as lateral approach distances for a mechanoid in a hallway. Additionally, it is of particular interest whether the robot's velocity significantly affects this threshold. In order to shed light on these questions, three hypotheses can be derived for the present study:

H1: The freely chosen minimal frontal distance will be greater than 0.45m and therefore outside of the intimate zone.

H2: The freely chosen minimal lateral distance will be smaller compared to the chosen frontal minimal distance.

H3: The faster the velocity of the approaching mechanoid, the bigger the freely chosen minimal frontal and lateral distance.

III. Method

A. Participants

A total of N = 35 subjects participated in the experiment, 18 (51.4%) were female and 17 (48.6%) male. Their age ranged from 24 to 59 years (M = 33.69, SD = 9.83), 33 subjects were German, one was Croatian and one American. 24 participants had a non-technical professional background (68.6%) opposed to 11 participants who had a rather technical professional background (31.4%). The majority of the subjects (85.7%) did not practice professional or leisure activities with any kind of autonomous systems. Lastly, 21 (60.0%) subjects had never seen the used robotic prototype before, nine (25.7%) already saw it in pictures or videos and just five (14.3%) subjects had real prior experience with it. All participants received a 30€ voucher for their participation.

B. Material

The present study was conducted in the robotic lab of the Robert Bosch GmbH in Schwieberdingen, Germany. The lab was divided by a wall covered with white film and had a door-like entrance. Entering induced a feeling of being in a hallway with white walls - here the actual experiment took place. The simulated hallway was six metres long and 2.90m wide. These dimensions were chosen to ensure a sufficient amount of space regarding the experimental variations. Blue markings on the ground indicated the starting position of the robot and two different subjects' positions according to the corresponding experimental condition. In the experimental conditions exploring frontal distances the robot started 4.5m in front of the subjects. Conditions comprising lateral distances marked a subjects' starting position 3.2m in front of the robot and with a lateral off-set of 1.2m. The robot used was a prototypic cuboid-like mock-up body attached to an omni-directional mobile platform (youBot) provided by KUKA Roboter GmbH (see Fig.1). The technical equipment was covered by a prototypic semi-transparent white shell (the mock-up body). In the front, a black display was attached which, was without any function for the experiment. The entire robot prototype was 0.73m long, 0.46m wide and 1.05m high. Acceleration values were set to 2m/s² and -2m/s² resulting in fast stopping and accelerating without big lags. Two Hokuyo laser range finders (UTM-30LX) were attached to the body in different heights (0.27m and 0.97m), enabling to detect the robot's surroundings in different height levels with a 270° angle of scan. For the distance measurement of the dependent variables the higher attached laser range finder was used. It captured the subjects' hips, respectively belly region which was beneficial for subsequent data analysis. This laser range finder was placed in the body centre on top of the shell. Using the robot's on-board sensors to measure distances, even in an experimental setup, is beneficial in terms of data accuracy as well as ecological validity compared to formerly applied methods of distance measurement, e.g. by using a grid on the floor or subsequent video analysis [5]. Additionally, a remote control device for the robot – a Logitech wireless gamepad F710 with two analog control elements – was used to provide participants with the opportunity to control the prototype's movement.

Figure 1. Bosch Mechanoid

C. Procedure

First, subjects were informed about the scope of the study and data privacy. They were also introduced to the robot and were briefed regarding its potential future functionality. A possibly negative association with the term 'robot' was taken into account for the entire experiment. Therefore, instead of robot, the term 'autonomous assistant' was used. Subsequently participants were asked to complete a preliminary questionnaire. They received the general instruction, asking them to move either the robot or themselves until reaching the minimal frontal or lateral distance just before it starts to feel uncomfortable (see Fig. 2 for the experimental setup). Moreover, they were briefed that they should absolutely spontaneously come to a decision according to their own discretion. Afterwards the main part of the experiment started. The examiner navigated the robot via remote control to its starting position on one end of the hallway and briefed the subjects about how to control the robot. In each condition the subjects remotely controlled the robot. Since the participants exclusively had to start and stop the robot, all other control options (e.g. steering, turning sideways, changing speed) were disabled, resulting in an easy operation for the remote control that was mastered by all participants without any difficulty. Independent of the chosen controller intensity the robot would always drive at the predetermined speed. Before starting off with the first experimental condition subjects had to get used to the controls by conducting several practice runs (accelerating and decelerating). In the course of the experiment the robot was returned to the starting position by the examiner after each trial. Furthermore, the examiner always indicated the new starting position for the subjects depending on the upcoming experimental condition. Subsequently the subjects went on with the next trial. Before each trial the examiner left the hallway setting and remotely adjusted the appropriate speed level of the robot.

During all frontal distance conditions subjects were asked to drive the robot towards themselves and stop it as soon as they started feeling uncomfortable without correcting the robots position after the initial stop. During the lateral distance conditions they were asked to position themselves along a marked line on the floor as close to the passing robot as it starts getting uncomfortable without correcting their own initially chosen position. It is important to note that participants were instructed to start with their own positioning as soon as they started to drive the robot towards themselves. Due to the minimized control functions the robot could only be driven along the exact same way. All in all subjects had to undertake eight different experimental conditions. The entire experiment lasted approximately 30minutes and at the end subjects had the possibility to indicate desires, remarks or other comments regarding a possible market-ready transport robot.

D. *Experimental Design*

In order to increase the reliability of the measured distances as well as to get insights into potential habituation effects, two identical experimental blocks were conceptualized. Both blocks comprised the same two within-subject variables: (IV1) type of distance (FD – frontal distance and LD – lateral distance) and (IV2) velocity (v1 = 0.6m/s and v2 = 0.8m/s). Velocities above 0.8m/s could not be tested due to technical restrictions of the prototype. Thus, the 2x2 study design consisted of four diverse experimental conditions resulting in eight trials in total due to the repetition. The order of conditions was randomized in each experimental block. It is noteworthy that the design avoided two identical conditions in sequence. All experimental conditions are labeled according to their within-subject factor and their time of presentation in the randomly assigned setup (LD1_v1 = first time exposure to the lateral condition with a velocity of 0.6m/s; LD2_v2 = second time exposure to the lateral condition with a velocity of 0.6m/s; etc.) As dependent variables the measured lateral distance (DV1) or frontal distance (DV2), that reflected the threshold to comfort, were assessed for each trial.

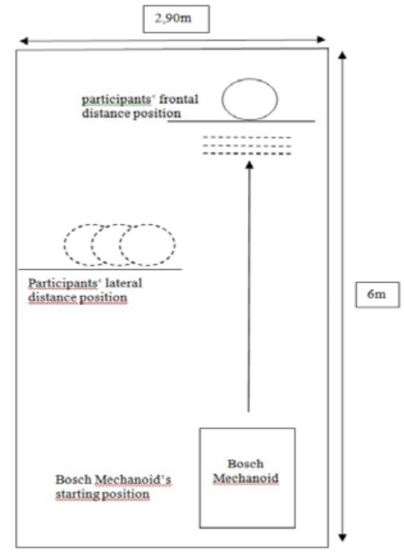
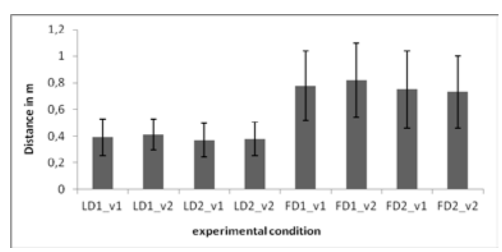


Figure 2, the experimental setup

IV. Results

With respect to the assessed DVs (lateral and frontal distance), the recorded data of the upper laser range finder were analyzed. For computing the absolute minimum distance between the robot and the human the nearest point of the human, except any arms or manipulators reaching out, was derived from the recorded data. Subsequently the data analysis script subtracted the robots' body shell dimensions from the gained distance resulting in the absolute distance between the closest point of the participants' hip (lateral conditions) or belly region (frontal conditions) and the robot's shell.

Fig. 3 provides an overview of the gained findings. The results including all assessed mean distances and the corresponding standard distributions are illustrated.



:e
measurements

In order to explore whether significant differences exist between the means, paired t-tests were computed. Significant differences were obtained in the scores for all lateral distance conditions and frontal distance conditions (see Table 1). The maintained frontal distances were always higher compared to the correspondent lateral distances. Additionally, the mean lateral distance (M=0.40m, SD=0.125m) and mean frontal distance (M=0.77m, SD=0.275m) were assessed.

A further finding concerns the distribution of measured lateral and frontal distances as well as the correspondence to the personal space zones according to Hall [15]. The majority of the subjects (> 70%) preferred a minimum frontal distance within the personal zone according to Hall's categorization (0.45 to 1.2m). Taken this 70% as a reference and applying it to the lateral distance distributions, the following boundaries for a possible lateral zone categorization were derived: zone #1 ranging from 0.0m to 0.25m, zone #2 ranging from 0.25m to 0.55m and zone #3 starting at 0.55m. With respect to the lateral distance distributions, the majority of the subjects (> 70%) preferred a minimum lateral distance within zone #2.

TABLE I. DIFFERENCES IN LATERAL AND FRONTAL TRIALS

Trial	Mean (M)	Standard Deviation (SD)	t(34)	p
First Time Lateral Distance and 0.6m/s (LD1_v1)	0.39	0.14	-9.932	0.000
First Time Frontal Distance and 0.6m/s (FD1_v1)	0.78	0.26		
Second Time Lateral Distance and 0.6m/s (LD2_v1)	0.37	0.13	-9.192	0.000
Second Time Frontal Distance and 0.6m/s (FD2_v1)	0.75	0.29		
First Time Lateral Distance and 0.8m/s (LD1_v2)	0.41	0.12	-9.478	0.000
First Time Frontal Distance and 0.8m/s (FD1_v2)	0.82	0.28		
Second Time Lateral Distance and 0.8m/s (LD2_v2)	0.38	0.12	-8.299	0.000
Second Time Frontal Distance and 0.8m/s (FD2_v2)	0.73	0.27		

To fathom the third hypothesis, further paired t-tests were computed. Between all comparable experimental treatments regarding the robot's velocity neither significant differences in the mean distances (p > 0.05) nor significant trends (p > 0.1) occurred.

With respect to the repetition of each condition only some significant differences were obtained which are shown in Table 2.

However, with regard to the second lateral pair no significant difference was obtained for LD1_v2 (M=0.41, SD=0.12) and LD2_v2 (M=0.38, SD=0.12), t(34) = 1.720, p = 0.094. Moreover, presented frontal conditions with a velocity of 0.6m/s (FD1_v1 and FD2_v1) did not significantly differ in their scores.

TABLE II. DIFFERENCES IN REPEATED TRIALS

Trial	Mean (M)	Standard Deviation (SD)	t(34)	p
First Time Lateral Distance and 0.6m/s	0.39	0.14	2.312	0.027
Second Time Lateral Distance and 0.6m/s	0.37	0.13		
First Time Frontal Distance and 0.8m/s	0.82	0.28	2.748	0.01
Second Time Frontal Distance and 0.8m/s	0.73	0.27		

Lastly, all gathered control variables (professional background, prior robot experience, etc.) did not significantly affect the dependent variables except a significant gender effect which was obtained for frontal distances. This finding is based on a computed MANOVA with the same independent variables and gender serving as a between-subject variable. With respect to the FD1_v1 male subjects accepted smaller distance on average (M= 0.68, SD=0.25) compared to female subjects (M= 0.88, SD=0.24), F(1,39)=5.691, p=0.023. Similar effects were obtained for FD1_v2: on average, male subjects accepted smaller distances (M= 0.71, SD=0.24) compared to female subjects (M= 0.94, SD=0.28), F(1,39)=6.572, p=0.015. Again, similar effects were found for FD2_v1 (male subjects: M= 0.66, SD=0.33, female subjects, M= 0.84, SD=0.23, F(1,39)=3.286, p=0.079) and FD2_v2 (male subjects: M=0.61, SD=0.27, female subjects: M=0.85, SD=0.23, F(1,39)=7.662, p=0.009). However, a similar gender effect was not observed in the lateral distance conditions.

A. *Discussion*

The goal of the present study was to determine a potential threshold of comfort in human-mechanoid spatial interaction. The focus was specifically set to explore frontal and lateral distances in a hallway scenario. For this purpose a user study putting the users in control of the mechanoid was conducted in a laboratory hallway-like setting.

All gained single frontal distance means were bigger than 0.45m as was assumed in the first hypothesis, supporting the stated assumptions of H1. Therefore, the postulated intimate zone by Hall [11] seems to exist in HMP as well. However, no conclusions regarding the size of this zone in HMP can be derived from the present examination. Whether the threshold of comfort also identifies the threshold of the personal zone should be subject of investigation for future studies. Furthermore, the chosen frontal means indicate that the participants did not see the mechanoid as a close friend or family member in terms of the intimate zone conventions derived from HHI. In addition, the gained frontal means are partly in accord with former conducted empirical studies regarding human-robot proxemics [25]. Even though, as already stated in the related work section, diverse robotic prototypes and distance measurement techniques were applied in other studies, similar mean frontal distances were obtained (robot to human approach at approximately 0.88m) [25]. Moreover, in study [26], frontal mean distances were mostly outside of the intimate zone, additionally supporting hypothesis 1 as well as the observed means in the present study. Obtained distributions of frontal distances were in accord with previous findings [26], showing that preferred frontal distances in HRI are mainly within the personal zone.

In the present research the scores for frontal mean distances turned out to be significantly higher compared to lateral mean distances among all experimental conditions. The computed overall frontal mean is almost twice as big as the overall lateral mean. Thus, these findings provide support for the second hypothesis.

With respect to a lateral spatial zone categorization, initial indications can be derived from the present findings: The undertaken analysis of frequencies concerning the lateral and frontal distances provided further insights into a possible categorization of lateral personal space zones in human-mechanoid interaction. When applying the distributions of the chosen frontal distances to the lateral distances, the majority (> 70%) of selected lateral distances occurred in the range between 0.25m and 0.55m. Assuming this range is to some extent comparable to the postulated frontal personal zone, the present findings provide first insights into a possible quantification of a lateral personal zone or, in other words, a so called second spatial zone after a first one. Along this line of argumentation it can be further stated that a possible quantification of an intimate zone (or zone #1) for lateral distances ranges from 0.0m to 0.25m and correspondingly, that a social zone (or zone #3) starts at 0.55m. Thus, these findings shed a first light on an exploration of lateral spatial zones in terms of quantification. Nonetheless, these findings can only be interpreted as a first starting point in an iterative process of further studies focusing on the exploration of lateral personal space zones. Taken these and previous results as a basis for interpretation, it can be stated that a mechanoid should respect certain spatial thresholds, i.e. it should not come too close. The mechanoid seems to be seen by humans as a social actor comparable to a working associate in terms of spatial interaction. Furthermore, again in line with previous findings [5],[8], the general relevance of human-robot proxemics is supported by the present study. Nonetheless, it should be noted that the height and design of the machine-like prototype used affected both the chosen frontal and lateral distances. Indications of a significant impact of body height on personal space have already been noted in human-human interaction experiments. Across several studies, it was observed that humans stop farther away from tall persons than from short persons. Thus, an increased height of the relatively small Bosch mechanoid might change the subjects' feelings and increase the corresponding personal space thresholds, or conversely, lead to a decreased threshold if the robot used is even smaller. This relation needs to be explored in future experiments. In addition, it is essential to emphasize that the attained parameters are not a general result, and are of limited applicability due to the limited experimental conditions. By using diverse robots and altering their designs in future work, the authors will aim to gain more general information about the relationship between robot design and personal space.

With respect to the third hypothesis, a variation of the mechanoid's velocity did not significantly affect the chosen threshold of comfort in terms of chosen frontal and lateral mean distances. Thus, the third hypothesis needs to be rejected. Although there is a fairly huge body of existing research indicating and empirically proofing an interaction of velocity and distance [e.g. 35], no significant interaction effects were found in the present study. The authors assume that this occurred due to an insufficient experimental variation. The difference between v1=0.6m/s and v2=0.8m/s might be too small in order to significantly affect the chosen distances. Unfortunately, no faster velocity than v2 could be investigated due to technical constraints. A possible explanation might be based on the general speed range. Perhaps v1 and v2 are both in the preferred range of velocities and therefore do not lead to significant effects on the ensuing personal space. From previous work [6], slower velocities than v1 were expected to be perceived as too slow. In contrast to previous studies, only behavioral data (objective data) and no subjective perceptions of the subjects were recorded. Therefore, no statements can be derived concerning the subjects' perceived comfort level of the diverse velocities. However, despite the non-supportive findings regarding the third hypothesis, future work should further investigate a potential interaction between distance and velocity. By additionally gathering subjective perceptions and increasing experimental variations previous findings could be replicated as well as completed.

With regard to the shown significant main effect in habituation (repetition of the experimental conditions), with the exception of one pair of conditions (frontal distance, velocity of 0.6m/s), results suggest that people get used to robots very fast, and this in turn significantly affects their spatial threshold of comfort. Among all significant pairs of conditions the mean distances already significantly decreased during the second presentation of the same experimental treatment. This is in line with reported habituation effects in related work [26]. Therefore, future long-term studies considering human-robot spatial interaction should be conducted in order to shed light on the power of habituation and its impacts on spatial behavior. Since it is impossible to capture a person's degree of habituation to a robot by a sensor, gathering certain habituation patterns of diverse target populations would be helpful for adapting the robotic behavior to a specific environment.

Lastly, the found significant main effect for gender is seen as a further empirical contribution to previous gathered findings. Gender influences on personal space were postulated in HHI literature [12]. The present study provides empirical evidence regarding this effect for HRI. Female humans prefer a bigger frontal distance compared to male humans. Nonetheless, this effect did not occur among the lateral conditions. It is assumed by the authors that the lateral personal space area might be less sensitive for humans compared to the frontal area: With respect to lateral conditions, the robot did not follow a path heading straight towards the human, possibly inducing a higher feeling of safety for the human. On the other hand, in the frontal conditions the humans' permanent intention to avoid

V. CONCLUSION

To sum up, the present work aligns to previously conducted research supporting a general relevance of human-robot proxemics (personal space) in human-robot interaction. It is interesting to note that a threshold of comfort for frontal as well as lateral distances exists in human-mechanoid interaction in a hallway scenario. Specific values for frontal as well as lateral thresholds were explored and quantified. With respect to the practical implications of the study results, one main conclusion for roboticists comes up: they should be aware of prevailing spatial thresholds of comfort a social robot should not violate if possible, and integrate them into future software frameworks. The authors believe that determining a threshold of comfort is a valuable starting point for transferring/implementing scientific human-robot proxemics results into real products. In addition, the present study provides first insights into a possible categorization of the lateral personal space area of humans, and explores how certain findings regarding the frontal personal space area could be transferred to the lateral area. In contrast to related work, no interaction effects of velocity and personal space occurred. Next to previously mentioned future research questions it is of special interest for the authors to further explore the determined thresholds for the case of an autonomous robot function that cannot be controlled by the subjects. A future evaluation of the thresholds incorporating an autonomously acting mechanoid is seen as an important next step in order to increase the ecological validity. Finally, it is important to note that all observed findings and interpretations are only valid for the reported study.

REFERENCES

[1] C. Bartneck and J. Forlizzi, "A design-centred framework for social human-robot interaction," in *Proc. of the RO-MAN*, Kurashiki, Okayama Japan, 2004, pp. 591–594.

[2] K. Dautenhahn, "Socially intelligent robots: dimensions of human–robot interaction," *Philosophical Transactions,* R. Soc. B 362, pp. 679–704, 2007.

[3] T. Fong, I. Nourbakhsh, K. Dautenhahn, "A Survey of Socially Interactive Robots: Concepts, Design, and Applications," Technical Report CMU-RI-TR-02-29, Carnegie Mellon University, Pittsburgh, USA, 2002.

[4] H.J. Böhme, "Serviceroboter und intuitive Mensch-Roboter-Interaktion," Habilitation, Technische Universität Ilmenau, Ilmenau, Germany, 2001.

[5] M.L. Walters, "The Design Space for Robot Appearance and Behavior for Social Robot Companions." Ph.D. dissertation, University of Herfortshire, Herfortshire, UK, 2008.

[6] E. Pacchierotti, H.I. Christensen, P. Jensfelt, "Human robot embodied interaction in hallway settings: a pilot user study," in *Proc. of the IEEE Int. Workshop on Robot and Human Interactive Communication*, Nashville, TN, USA, 2005.

[7] B. Mutlu and J. Forlizzi. "Robots in Organizations: The Role of Workflow, Social, and Environmental Factors in Human-Robot Interaction," in *Proc. of HRI'08*, Amsterdam, 2008, pp. 287-294.

[8] R. Kirby (2010), "Social Robot Navigation," Ph.D. dissertation, The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania, 2010.

[9] R. Sommer, *Personal space: the behavioral basis of design*. New Jersey: Prentice-Hall, 1969.

[10] E.T. Hall, *The Hidden Dimensions: Man's Use of Space in Public and Private*. The Bodley Head Ltd, London, 1966.

[11] E. T. Hall, "Proxemics," *Current Anthropology*, vol. 9(2-3). pp. 83-108, 1968.

[12] J. K. Burgoon and S. B. Jones, "Toward a Theory of Personal Space Expectations and Their Violations," *Human Communication Research*, vol. 2(2). pp. 131-146, 1976.

[13] L. O. Stratton, D. J. Tekippe, G. L. Flick, "Personal Space and Self Concept," *Sociometry*, vol.36., pp. 424-429, 1973.

[14] D. L. Gillespie, A. Leffler, "Theories of Non-Verbal Behavior: A Critical Review of Proxemics Research," *Sociological Theory*, vol. 1, pp. 120-154, 1983.

[15] D. Chen, J. Yang, H.D. Wactlar, "Towards automatic analysis of social interaction patterns in a nursing home environment from video," in *Proc. 6th ACM SIGMM International Workshop on Multimedia Information Retrieval*, New Yorck, NY, 2004, pp. 283–290.

[16] E. Goffmann, *Relations in Public: Microstudies of the public Order*. Basic Books, Inc., Publishers, New Yorck, 1971.

[17] G. Barney, *Elevator traffic handbook (theory and practice)*. Taylor & Francis, New Yorck, 2003.

[18] O.M. Watson, *Proxemic Behavior: A Cross-Cultural Study*. Mouton, The Hague, 1970.

[19] S. N. Woods, K. Dautenhahn, J. Schulz (2004), "The Design Space of Robots: Investigating Children's Views," in *Proc. of 13th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN 04),* Kurashiki, Okayama Japan, 2004, pp. 47-52.

[20] N. Bellotto, M. Hanheide1, N. Van de Weghe, "Qualitative Design and Implementation of Human-Robot Spatial Interactions," *Social Robotics*, Lecture Notes in Computer Science Volume 8239, pp. 331 -340, 2013.

[21] M. L. Walters, D.S. Syrdal, K. Dautenhahn, R. te Boekhorst, K.L. Koay, (2008). "Avoiding the uncanny valley: robot appearance, personality and consistency of behavior in an attention-seeking home scenario for a robot companion," *Auton Robo*, vol. 24, pp. 159–178, 2013.

[22] J. Mumm and B. Mutlu, "Human-Robot Proxemics: Physical and Psychological Distancing in Human-Robot Interaction," in *Proc. of HRI'11*, Lausanne, 2011.

[23] K. Dautenhahn , M. Walters , S. Woods , K. L. Koay , C. L. Nehaniv, E.A. Sisbot, R. Alami, T. Simeon, "How May I Serve You? A Robot Companion Approaching a Seated Person in a Helping Context," in *Proc. of HRI'06*, Salt Lake City, Utah, USA, 2006, pp. 172-179.

[24] J. Kessler, C. Schroeter, H.M. Gross, "Approaching a Person in a Socially Acceptable Manner Using a Fast Marching planner." in *Proc. of 2011 International Conference on Intelligent Robotics and Applications (ICIRA)*. Aachen. Germany, 2011, pp. 368-377.

[25] M. Walters, K. Dautenhahn, C. Kaouri, R. Boekhorst, C. Nehaniv, I. Werry, D. Lee, "Close encounters: spatial distances between people and a robot of mechanistic appearance," *in Proc. of 5th IEEE-RAS International Conference on Humanoid Robots*, Japan, 2005, pp. 450-455.

[26] H. Huettenrauch, K. Severinson Eklundh, A. Green, E.A.Topp, "Investigating Spatial Relationships in Human-Robot Interaction," in *Proc. of the 2006 IEEE/RSJ International Conference on Intelligent Robots and System,* Beijing, China, 2006, pp. 5052-5059.

[27] M. Lohse, *Nutzerfreundliche Mensch-Roboter Interaktion. Kritierien fuer die Gestaltung von Personal Service Robots*. Saarbruecken, VDM Verlag Dr. Mueller, 2007.

[28] O. Morgenroth, *Zeit und Handeln. Psychologie der Zeitbewältigung*. Stuttgart, Kohlhammer, 2008.

[29] M. Saerbeck, and C. Bartneck, "Perception of Affect Elicited by Robot Motion," in *Proc. of 5th ACM/IEEE International Conference on Human-Robot Interaction (HRI2010),* Osaka, Japan, 2010, pp. 53-60.

[30] K. Dautenhahn, S. N. Woods, C. Kaouri, M. L. Walters, K. L. Koay, I. Werry, "What is a Robot companion - Friend, Assistant or Butler?," *In Proc. of IROS'05*, Alberta, Canada, 2005, pp. 1192-1197.

[31] J.T. Butler and A. Agah, "Psychological Effects of Behavior Patterns of a Mobile Personal Robot," *Autonomous Robots*, vol. 10, pp.185-202, 2001.

[32] A. Sardar, M. Joosse, A. Weiss, V. Evers, "Don't Stand so Close to Me: Users' Attitudinal and Behavioral Responses to Personal Space Invasion by Robots," in *Proc. of HRI'12*, Boston, Massachusetts, USA, 2012.

[33] A. Branzell and Y.C. Kim, *Visualising the invisible. Field of perceptual forces around and between objects*. Göteborg, Design Methods, Department of Building Design, 1995.

[34] R. Kirby, R. Simmons, J. Forlizzi, "COMPANION: A Constraint-Optimizing Method for Person–Acceptable Navigation," in *Proc. of The 18th IEEE International Symposium on Robot and Human Interactive Communication*, Toyama, Japan, 2009.

[35] H. Mizoguchi, T. Sato, K. Takagi, M. Nakao, Y. Hatamura, "Realization of Expressive Mobile Robot," *in Proc. of 1997 IEEE International Conference Robotics and Automation*, Albuquerque, NM, 1997, pp. 581-586.

[36] M.E. Caplan and M. Goldman, "Personal Space Violations as a Function of Height." *The Journal of Social Psychology*, vol. 114, pp. 167-171, 1981.
[37] J.J. Hartnett, K.G. Bailey, C.S. Hartley, "Body Height, Position, and Sex as Determinants of Personal Space" *The Journal of Psychology*, vol. 87, pp. 129-136, 1974.