Human-Robot Spatial Interaction in a Hallway

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Abstract

In general, previous research in human-robot interaction has provided evidence for the relevance of robotic motion behavior on positive impressions towards robots. In particular, a socially appropriate designed robotic distance behavior, avoiding personal space violations, has been reported to be essential for a comfortable human-robot spatial interaction. Unfortunately, human-robot proxemics lacks systematic explorations of accepted frontal approach and lateral passing distances in a hallway, and existing studies are complicated to relate to each other due to the application of many different robots and a high variance of further incomparable study details.

Thus, the primary research goal of this dissertation was to explore accepted frontal approach and lateral passing distances for an autonomously moving robot toward a standing human in a hallway, and supplementary, the relation of these distance preferences to the robot's level of speed and human likeness. In addition, the present work intends to explore the relevance of a robot's proxemic behavior for its overall motion acceptance, and people's underlying psychological motives guiding their preferences.

Towards an exploration of these research objectives, a method comprising a series of three studies was conceptualized and conducted in comparable hallway-like settings. In a first study, participants were instructed to actively control a robot's frontal approach and its lateral passing distance according to their arousing feelings of discomfort. In two successive studies, the analyzed thresholds of comfort were validated for two diverse robots, autonomously maintaining frontal approach and lateral passing distances in a hallway. In addition, potential influences of a robot's level of speed (0.6m/s, 0.8m/s) and human likeness (machine-, human-like) on subjects' distance preferences were explored. In these studies, participants' sensations were captured by using a set of questionnaires.

Obtained results uncovered that accepted frontal approach (approximate 0.8m) and lateral passing mean distances (approximate 0.4m) towards autonomously moving robots in a hallway exist, and that these distances were not significantly affected by the simulated autonomy of the robots. However, a faster robot speed (0.8m/s) significantly increased subjects' distance preferences. The different outward robot designs of the employed robots had no significant influence on subjects' frontal distance preferences. In contrast, the manipulated level of human likeness showed that a more human-like robot design had only

significant influences on subjects' lateral distance preferences when a real human face was projected on a robot's screen (decrease in lateral distances by more than 0.1m). Essentially, in line with previous research, the present work shows that a socially acceptable moving robot should consider people's distance preferences in order to avoid feelings of discomfort, and to increase the perceived safety and the overall motion acceptance. In consensus with prevailing psychological motives in human-human spatial interactions, the present work suggests similar mechanisms in a human-robot spatial interaction guiding subjects' preferences. Ultimately, beyond the attained mean distances, frontal approach distances of 1.1m and lateral passing distances of 0.6m were suggested for designing a socially appropriate first contact for a large majority of individuals, which in turn supports a facilitated societal integration. Limitations of this research project are discussed and suggestions for future investigations are presented.

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List of Abbreviations

α	–	significance level
ANOVA	–	analysis of variance
MANOVA	–	multivariate analysis of variance
cf.	–	compare
et al.	–	et alia: and others
e.g.	–	for example
etc.	–	et cetera
F	–	F statistic (test value)
HHI	–	human-human interaction
HRI	–	human-robot interaction
HHP	–	human-human proxemics
HRP	–	human-robot proxemics
HRSI	–	human-robot spatial interaction
i.e.	–	that is
M	–	mean
n	–	sample size
SD	–	standard deviation
SEM	–	standard error of the mean
t	–	t statistic (test value)
p	–	probability
ROS	–	robot operating system

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Some thirty inches from my nose
The frontier of my person goes,
And all the untilled air between
Is private pagus or demesne.
Stranger, unless with bedroom eyes
I beckon you to fraternize,
Beware of rudely crossing it:
I have no gun, but I can spit

W.H. Auden, “Prologue: The Birth of Architecture” (cited in Hall, 1966)

1 Introduction

Whenever I tell people about my work with robots, many react with astonishment, fascination, skepticism, fear, or something in between. Why is this? We need to travel back in time to find answers.

The term *'robot'* initially appeared in a Czech sciene fiction role play in 1920 (Čapek, 2004). In it, robots were described as artificial humans that eventually became hostile towards their human co-workers and wiped out the whole of humanity (Longyear, Asimov & Ford, 1979; Čapek, 2004). This stigma has been nourished over the course of the second half of the last century, regardless of robots' actual fate of performing simple repetitive tasks in dark factory cages (Thrun, 2004). Along with tremendous technological progress throughout the past 20 years (Scholtz, 2003; Kwak, Kim & Choi, 2014), novel areas of robotic applications in complex human environments have gradually emerged. However, this new era of service and social robots is far away from revolting against mankind. In fact, one of the most advanced research robots of our time – the PR2 – has been described as *'dumber than a doornail'* by the developing company's founder (The Economist, 2014). This new sort of robot assists humans in their daily tasks at home or at work, such as delivering goods of various kinds in hospitals (Aethon's TUG, 2014) or hotels (Savioke's SaviOne, 2014) (Thrun, 2004). For a first time in robotic history, it is now expected that these robots should possess social capabilities in addition to their technical functionality (Walters, 2008). By having them exhibit socially appropriate behavior, developers aspire to create robots that avoid disturbing, annoying or scaring humans (Walters, 2008). But what does it take for these new robots to comfortably, trustfully, and effectively collaborate with humans?

This poses the central research goal of a fairly young scientific discipline – human-robot interaction (HRI). To date, many prevailing scientific debates regarding robotic appearance, behavior and their interrelationship occupy the scientific community. Particularly, designing an adequate outward robot appearance has been a prominent, but largely unexplored subject (Hinds, Roberts & Jones, 2004; Walters, 2008). On the other hand, aspects of a socially adequate non-verbal behavior, such as robotic motion behavior, have been significantly less addressed and systematically explored yet (Woods, Dautenhahn & Schulz, 2004; Brooks & Arkin, 2007; Walters, 2008; Mumm & Mutlu, 2011). Given the pivotal relevance of non-verbal communication in human-human interaction (HHI) (Birdwhistell, 1952; Watzlawick, 2011), this imbalanced research attention is quite surprising. As well observable in everyday life, humans possess the remarkable capability of coordinating and optimizing their space in a non-verbal and non-random way (Bennewitz, 2004; Weiss, Mirnig, Buchner, Förster & Tscheligi, 2011). In fact, humans can fairly well predict mutual trajectories and avoid bumping in to each other without exchanging a single word (Frith & Frith, 2006; Crick, Doniec & Scassellati, 2007). The corresponding scientific discipline, addressing personal and interpersonal distance, is called proxemics (Hall, 1966). Though humans are not consciously obeying underlying spatial rules, this mechanism substantially structures and affects people's daily interactions (Hall, 1966; Marquardt & Greenberg, 2012).

Think about your last situation in a very common human environment, a hallway. How close did another person frontally approach you while standing in a hallway? How close did another person pass by you while standing in a hallway? Although you presumably cannot recall a precise distance, the other person probably avoided a collision and gave you sufficient personal space.

By replacing the other person with a robot, inevitably, the thought-provoking question arises whether a robot should consider and obey human spatial conventions as well. This is subject of a crucial sub-domain of HRI – human-robot spatial interaction (HRSI) (Bellotto, Hanheide & Van de Weghe, 2013). In particular, the field of human-robot proxemics (HRP), which poses a key feature of HRSI, studies the distance behavior between humans and robots (Asghari Oskoei, Walters & Dautenhahn, 2010). Past research has already obtained initial indications regarding humans' sensitivity toward robotic spatial behavior (Mutlu & Forlizzi, 2008; Walters, 2008). In particular, field and lab studies have shown that robots, approaching humans inappropriately closely, caused feelings of discomfort or even threat (Walters, 2008; Mutlu & Forlizzi, 2008). Accordingly, researchers have suggested that an adequately designed robotic distance behavior is of vital relevance for a seamless societal integration (Takayama & Pantofaru, 2009; Mumm & Mutlu, 2011). Nonetheless, though these studies have provided some evidence for the relevance of socially appropriate robotic distance behavior, numerous findings have been obtained in an ad-hoc manner and utilized incomparable methods. Thus, many uncertainties remain and diverse studies are rather complicate to relate to each other (Sauppé & Mutlu, 2014). Furthermore, commercially available systems rather focus on a safe, instead on a socially appropriate navigation (Mutlu & Forlizzi, 2008; Kirby, 2010).

To date, an exploration of accepted frontal approach and lateral passing distances toward an autonomously moving robot in a hallway has not been systematically conducted. Beyond this gap in research, the existing body of knowledge generally lacks systematic explorations of accepted lateral passing distances, a robot's proxemic behavior in a hallway, and underlying psychological motives in HRP. Furthermore, the influence of a robot's human likeness and speed on people's distance preferences has rarely been explored. Lastly, the relevance of an appropriately adjusted distance behavior of a robot for the overall motion acceptance has not been examined yet. Accordingly, these issues constitute the central focus of this dissertation and pose the framework for the successively formulated research goals and questions.

1.1 Research Goal

With regard to the overarching problem of this dissertation, the primary research goal is to systematically explore accepted frontal approach and lateral passing distances of an autonomously moving robot towards a standing human in a hallway. Supplementary, this work aims to examine potential dependencies of people's distance preferences to a robot's level of speed and human likeness. Beyond these objectives, this work examines the relevance of a robot's proxemic behavior for its overall motion acceptance, and provides further insights into the psychological backgrounds and motives guiding human-robot spatial interactions.

Taken together, findings are expected to be of high theoretical relevance for a broader understanding of HRSI, and are hoped to provide relevant practical implications for designing socially appropriate robotic motion behavior in a hallway.

1.2 Research Questions

1. Do frontal and lateral spatial thresholds of comfort exist during a human-robot spatial interaction in a hallway?

2. Which frontal mean distance does a standing person accept from an autonomously approaching robot in a hallway?

3. Which lateral mean distance does a standing person accept from an autonomously passing robot in a hallway?

4. Are these distance preferences also valid for another autonomously approaching or passing robot in a hallway?

5. Are people's distance preferences influenced by the robot's speed?

6. Are people's distance preferences influenced by a robot's level of human likeness?

7. Does the distance behavior of an autonomously moving robot affect the motion acceptance?

8. To what extent obey gained distance findings human spatial conventions?

1.3 Methodological Approach

Towards a systematic, reliable and valid exploration of the central research questions, a series of three experiments in highly comparable hallway-like settings was conducted.

To establish a robust empirical framework, the first study (N=35) initially explored accepted frontal approach and lateral passing distances by putting the participants in control of the transport assistant. In this study, standing subjects were instructed to adjust the frontal approach or lateral passing distance of a robot depending on their feelings of discomfort. In addition, the robot's level of speed was varied. Distance measurements were assessed by analyzing the attained laser data from the robot's on-board laser scanner. Subsequently, attained mean distances and assessed distance distributions provided the empirical reference for consecutive hypotheses and the developed autonomous distance calibration.

In the successive step – study II (N=40) – assessed distances from the first study were validated for an autonomously approaching or passing robot (transport assistant). In this experiment, participants were not in any control of the robot, instead, relatively precise pre-recorded motion trajectories were used to simulate the robot's autonomy. Importantly, this approach led to a higher accuracy of the maintained distances and was not noted by any participant. In sum, standing subjects were exposed to five diversely maintained frontal approach and lateral passing distances, and were requested to indicate their feelings by using a questionnaire upon each trial. For scrutinizing the formulated research questions, various relevant sensations were measured, such as the perceived proximity, discomfort, safety, human likeness and overall motion acceptance.

Ultimately, study III (N=40) was conceptualized to validate the attained distance findings from the second study for a different robot (Beam) autonomously approaching or passing a standing human in a hallway. Towards permitting a high comparability between study II and III, this experiment was aligned as much as possible to study II. Accordingly, participants were not in any control of the robot and were exposed to identical frontal approach and lateral passing distances. In addition, this study comprised the same instruction and questionnaires as study II. In the interest of achieving a relatively high distance accuracy in this experiment, the robot's autonomy was simulated by using a Wizard-of-Oz approach. As in study II, the simulated autonomy was not noted by any participant. Furthermore, the robot's level of human likeness was manipulated and its effect on participants' distance preferences was investigated.

1.4 Research Platforms

Throughout the conducted series of studies in this dissertation, two diverse machine-like looking robots are employed. Both are subsequently introduced and illustrated.

The first robot is a self-constructed and designed research prototype by Bosch. It is internally used for a wide range of soft- and hardware tests, and provides a manually and autonomously maneuverable research platform for conducting human-robot interaction experiments. This robot is named '***transport assistant***' throughout the entire dissertation and is shown in Figure 1-1.

Figure 1-1 Transport Assistant (Bosch Research Prototype)

In particular, the transport assistant comprises a prototypic cuboid-like mock-up body attached to an omni-directional mobile platform (youBot) provided by KUKA Roboter GmbH. The technical equipment is covered by a prototypic semi-transparent white shell (the mock-up body). In the front, a black display is attached which is without any function for all experiments in the present work and was constantly switched off. In total, the entire robot prototype is 0.73m long, 0.46m wide and 1.05m high. Two Hokuyo laser range finders (UTM-30LX) are 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. The upper laser range finder is placed in the body centre on top of the shell, and the lower one is placed above the left front wheel. By localizing itself based on laser data, the transport assistant can autonomously move in a hallway or in an open area. In addition, it is possible to remotely control its movements by using a Logitech wireless gamepad F710 with two analog control elements.

In contrast to the transport assistant and its rather prototypic characteristic, the second employed robot – **Beam** - is an already commercially available system by Suitable Technologies (Suitable Technologies, 2014). Essentially, it is a semi-autonomous telepresence system and can neither localize nor move autonomously. However, Beam posed an ideal second test platform for the purpose of this dissertation and was available at the Research and Technology Center of Bosch in Palo Alto, USA. Similar to the transport assistant, Beam also has a machine-like appearance as depicted in Figure 1-2.

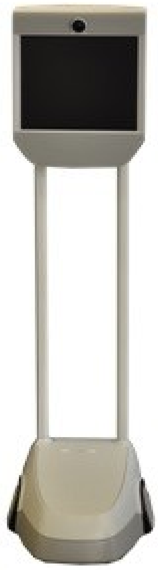

Figure 1-2 Beam (machine-like) (Suitable Technologies, 2014)

The system features a 17in screen, a six-microphone array enabling remote users to localize directions of sound, two wide-angle high resolution cameras (one front facing and one down facing), a digital zoom and two radio modules for seamless switching between access points on a wireless network. The battery time is reported to be long enough to last a full working day. Importantly, Beam can be controlled remotely from personal computers using keyboard or mouse devices. A typical interaction involves seeing and talking with the remote user's face as presented in Figure 1-3. This functionality is used for a manipulation of Beam's level of human likeness, which is discussed in greater detail in section 5.1.

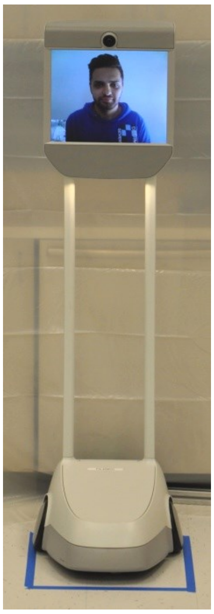

Figure 1-3 Beam (human-like version)

1.5 Structure of the Dissertation

Upon introducing the central research goals, questions and the pursued methodological approach of this dissertation, the successive part provides the theoretical foundation. Amid this chapter, briefly mentioned subjects of the introduction are presented in greater detail. The focus of this chapter is placed on HRSI and its core feature proxemics. First, related work and corresponding concepts of human-human proxemics are introduced and subsequently, human-robot proxemics research is reviewed. Upon summarizing the theoretical framework of this thesis, the empirical part, comprising a series of three studies, is presented. Ultimately, central findings are summarized and discussed in the overall discussion and conclusion.

2 Theoretical Foundation

Towards a classification and elucidation of relevant terms, theories, studies and methods for the present research project, this chapter provides the theoretical basis.

2.1 Robot Types

In this section, diversely developed robot types and their corresponding evolution of social requirements are introduced. This provides an explanative basis for the demand of HRI and HRSI research, respectively.

As already indicated in the introduction, the fast-paced technological advances in recent decades have caused an emergence of diverse types of robots. During the majority of robotic history, robots have never been integrated in human environments. First industrial robots have been placed in factories, strictly separated by cages and safety fences from their human co-workers (Thrun, 2004). Many people have most likely never seen one in reality, despite to date, industrial robots constitute the earliest and biggest commercial success within robotics (Thrun, 2004). However, they are the pioneers amid their more recently developed successors, and the first one was already operating by the early 1960s (Thrun, 2004). An acknowledged definition of an industrial robot is formulated by ISO 8373 (International Federation of Robotics, 2014), stating: '*…an automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications'*. Typical tasks embrace highly repetitive work steps, such as assembly work or packaging, by simply outperforming humans due to an increased accuracy, speed and lower costs (Smith, 2005).

Beyond the industrial cages in factories, progressive robotic advances led to a second robot type - service robots. They are defined by the International Federation of Robotics (2014) as *'... a robot that performs useful tasks for humans or equipment excluding industrial automation application. Note: The classification of a robot into industrial robot or service robot is done according to its intended application'*. Initial developments and areas of application mostly addressed hazardous or inaccessible environments for humans, for instance, robots exploring Mars or sweeping mines (Smith, 2005). Further applications rapidly poised to be integrated in humans' homes and workplaces, aiming to assist humans in their daily tasks, such as a robotic lawn mower, a vacuum cleaner or delivery robots in hospitals (Thrun, 2004). These service robots have been further subdivided into professional and personal service robots (International Federation of Robotics, 2014). Professional and personal relates to commercial or non-commercial tasks, assigning a hospital delivery robot to professional service robots and a domestic vacuum cleaner robot to personal service robots (International Federation of Robotics, 2014). In addition, it is claimed that professional service robots are usually operated by properly trained people in contrast to personal service robots (International Federation of Robotics, 2014). The term *'usually'* does not exclude all other kinds of people potentially encountering a professional service robot. Thus, the socially intrusive character of professional and personal service robots has not yet been adequately addressed in the definition of a service robot. Nonetheless, these robots have been the beginning of the prevailing robotic revolution by comprising the key challenge of acceptably adapting robots to a broad range of ordinary human environments, and thus, pose the transition to a novel era of robot types: social robots.

Social robots are envisioned to assist us at home, at work, at the supermarket, or even simply entertain us (Fong, Nourbakhsh & Dautenhahn, 2003a), and have been variously defined in existing literature. One commonly applied definition states that social robots are *'autonomous or semi-autonomous robots that interact and communicate with humans by following the behavioral norms expected by the people with whom the robot is intended to interact'* (Bartneck & Forlizzi, 2004, p. 593). Accordingly, the general approach of social robots strongly focuses on designing robotic companions which possess social skills in addition to classical robotic abilities (Smith, 2005). These robot companions are defined by Dautenhahn (2007, p. 685) as *'a robot that (i) makes itself 'useful', i.e. is able to carry out a variety of tasks in order to assist humans, e.g. in a domestic home environment, and (ii) behaves socially, i.e. possesses social skills in order to be able to interact with people in a socially acceptable manner'*. In Figure 2-1, essential criteria and their relation to each other regarding the demand of social skills, were illustrated by Dautenhahn (2007, p.683).

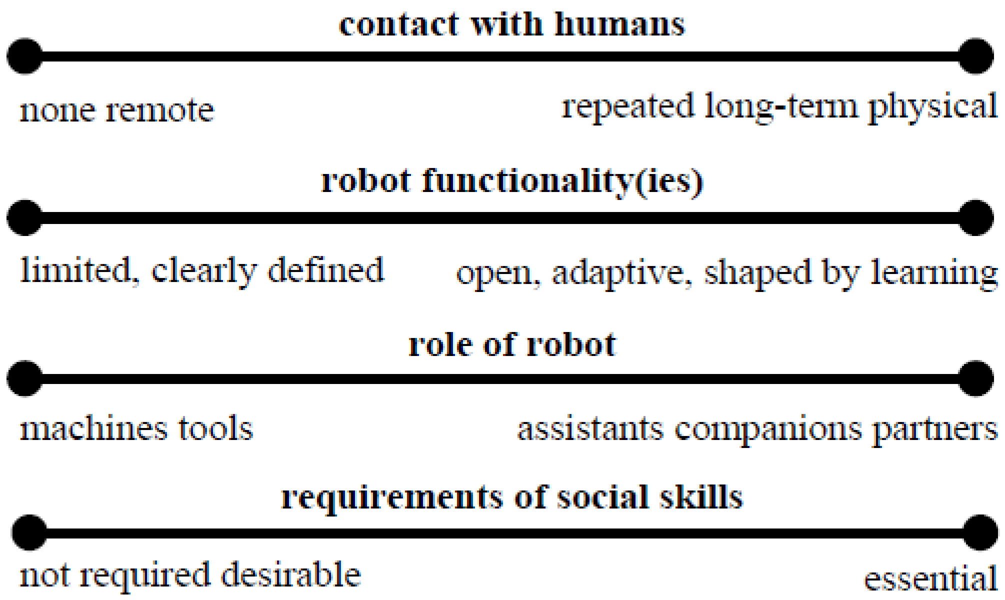

Figure 2-1 evaluation criteria for requirements on social skills (Dautenhahn, 2007, p. 683)

With regard to these postulations, service and social robots are no longer distinguishable. Each service robot, regardless of commercial or non-commercial tasks, should possess at least some social skills in order to successfully cooperate with people in heterogeneous human societies. Even industrial robots, the most traditional robot type, have been recently equipped with social capabilities allowing them to leave the security cage and collaborate more effectively and in closer proximity with humans (e.g. Baxter, Rethink Robotics, 2014). Those robotic systems have been frequently labeled as '*collaborative robots'*.

By transferring the introduced robot types and their differences to the present research context, the employed robotic systems can be categorized as social service robots. Due to their envisioned (transport assistant: hospital) or existing (Beam: office, museum, home) area of application, they demand social capabilities in addition to their technical functionality in order to be accepted by the entire human environment they shall operate in (Walters, Syrdal, Dautenhahn, Te Boekhorst & Koay, 2008a).

2.2 Human-Robot Interaction

With reference to the overarching scope of this dissertation, this section provides an overview of the scientific discipline human-robot interaction (HRI), including its definition and relevance for the previously introduced new era in robotics.

As already mentioned in the introduction, HRI is a fairly young field of research (Dautenhahn, 2013). Initial scientific publicity occurred in the early nineties and mainly focused on issues regarding industrial robots (e.g. Rahimi & Karkowiski, 1992; first IEEE RO-MAN conference in Japan). Along with a progressive intrusion of robots into complex human environments, novel robotic technology requirements have consistently developed, which in turn has led to a constant redefinition of HRI. Thus, it is not surprising that a universally valid definition of HRI has not yet been established (Lohse, 2007). In 2003b, Fong, Thorpe, and Baur (p.2) defined HRI as *'the study of the humans, robots, and the ways they influence each other'*. In the course of the following years, HRI definitions were formulated as more human-centered. In 2007, Lohse (p.20) stated *'HRI is an interplay of one or multiple humans with at least one robot, including all their available modalities. The goal of the discipline is to design the interplay as efficient, effective, and as user-friendly as possible.* To date, the most recent definition is postulated by Dautenhahn (2013), disclosing the continuously increasing richness of HRI: *'HRI is the science of studying people's behaviour and attitudes towards robots in relationship to the physical, technological and interactive features of the robots, with the goal to develop robots that facilitate the emergence of human-robot interactions that are at the same time efficient (according to the original requirements of their envisaged area of use), but are also acceptable to people, and meet the social and emotional needs of their individual users as well as respecting human values.'*

Nowadays, people who are confronted with robots are no longer exclusively system engineers or pre-instructed users (Böhme, 2001). All kinds of people, expert and non-expert users (Mutlu & Forlizzi, 2008), young and old persons (Broekens, Heerink, & Rosendal, 2009), healthy and handicapped people (Robins, Dautenhahn, Te Boekhorst & Billard, 2005) are involved with robotic applications. Thus, an everyday heterogeneous human society has to understand and accept interacting with this new sort of robot. This novel age of robots may collaborate on a very personal level with humans, for instance, help us in our home and become a part of our family (Jibo, 2014). Furthermore, social robotic systems are envisioned to autonomously deliver our mail and our food (Johnson, 2014), or drive our car (Markoff, 2014). Despite a commercialization is still due for these examples, HRI research has been suggesting great potential for currently available robotic products in diverse human domains, such as hospitals or retirement communities (Pollack, Brown, Colbry, Orosz, Peintner, Ramakrishnan, ... & Roy, 2002; Mutlu & Forlizzi, 2008; Aethon's TUG, 2014), hotels (Savioke SaviOne, 2014), museums (Shiomi, Kanda, Ishiguro, Hagita, 2007) or workplaces (Lauckner, Pangercic & Tuerker, 2015; Suitable Technologies' Beam, 2014).

With reference to all these robots, HRI pursues the central goal to design all aspects of the interaction as comfortable, intuitive and likeable as possible for all humans these robots share the environment with. Hence, as already uncovered in the latest definition of HRI (Dautenhahn, 2013), these robots need to possess social abilities in order to exhibit socially appropriate behavior, which in turn avoids disturbed, annoyed or even scared humans (Mumm & Mutlu, 2008; Walters, 2008). Even a so called *robotiquette* has yet been posit, which is defined as *'a set of heuristics and guidelines on how a robot should behave and communicate'* (Dautenhahn, 2007, p.686). Adequately designing the *robotiquette* is seen as a crucial core ingredient for better robot acceptance (Dautenhahn, 2007). In regard to a broad scope of social capabilities, it is of particular notice for this dissertation that several researchers have highlighted the importance of an adequately designed non-verbal behavior (e.g. Butler & Agah, 2001; Pacchierotti, Christensen & Jensfelt, 2006; Walters, 2008). Accordingly, establishing a socially acceptable interaction comprises aspects of verbal and non-verbal communication within this new epoch in robotics (Dautenhahn, 2007).

2.3 Challenges and Problems in HRI

This section provides an introduction to generally prevailing challenges and issues in HRI. Particularly, it highlights the relevance for attaining more generic results, which was pursued by the employed methodology of the present work.

Given a high complexity, multidisciplinarity and a vividly developing technology, research on HRI poses many challenges and problems. In accordance with no universally valid HRI definition, no generally accepted design guidelines regarding robotic appearance, behavior and corresponding methodologies have yet been elaborated (Dautenhahn, 2007). In contrast, many prevailing scientific debates regarding robotic appearance, behavior and their interrelationship occupy the scientific community to date.

Due to a high diversity within humans (e.g. personality, ethnos, demography), robots (e.g. type, appearance, functionality), and their interacting context (e.g. environment), the frequently applied key words in HRI, such as *'socially appropriate/adequate'*, *'socially intelligent'*, *'intuitive'* or *'natural'* often lack a precise meaning or strongly vary in their meaning. An examination of their contextual substance is in need of gaining insights into people's expectations and preferences, and corresponding psychological motives (Butler & Agah, 2001). By defining socially intelligent behavior as *'…includes dynamic reactions in real time, which meet the user's expectations in a given social context.'* Eyssel, Hegel, Horstmann, and Wagner (2010, p. 646) have provided explicit corroboration.

A wide range of inspirations and assumptions has been derived from comparable human-human interaction (HHI) contexts, which have been intensively explored by social sciences (Dautenhahn, 2007). Furthermore, HRI can also be linked to the field of human-computer interaction (HCI) providing further input, such as the media equation theory (Reeves & Nass, 1996). This theory contains the assumption that humans interact with computers, televisions and other media as if they interact with other humans (Reeves & Nass, 1996). However, though there are certainly some conveyable similarities between HHI/HCI and HRI, it is important to neither equal robots, nor computers with humans (Takayama & Pantofaru, 2009). Robots possess a physical embodiment and are autonomous, interactively operating in changing environments compared to stationary computers (Fong et al., 2003a). In addition, robots are not people (Dautenhahn, 2007), and it has been observed that people do not necessarily show similar social reactions to robots as they would show to other humans (Walters et al., 2008a; Sardar, Joosse, Weiss & Evers, 2012; cf. Rae, Takayama & Mutlu, 2012). For instance, in an experiment, participants were instructed to seek for information on a poster while either, a human-like robot or a human, joined them and purposely invaded their personal space (Sardar et al., 2012). Compensatory behavior, such as stepping or leaning away, was recorded and findings revealed that subjects displayed more of this sort of behavior towards the robot than towards the human. In addition, similar findings have been observed for animals and animal-like robots. In a study run by Friedman, Khan and Hagman (2003), participants' treatments and views towards a robotic dog (AIBO) were different from a real dog. Additionally, their research has shown that robots can be easily distinguished from living organisms, which leads to different engagements towards them (Friedman et al., 2003; cf. Takayama, 2009). Therefore, to date, it has remained inconclusive whether robotic technology in its diverse application contexts should completely adhere to human social conventions, paradigms and expectations known from HHI/HCI in order to establish a socially appropriate HRI (Takayama & Pantofaru, 2009). Nonetheless, to date, it has seemed to be a fascinating technical challenge to humanize robots by completely copying human behavior and physical appearance, regardless of people's actual expectations and preferences towards robots (Hinds et al., 2004; Ishiguro, 2007; Kirby, 2010; Kuderer, Kretzschmar, Sprunk & Burgard, 2012).

In addition, most HRI research has been rather practically driven (Lohse, 2007). A large body of empirical studies has addressed manifold interaction modalities, contexts and use cases. However, the majority of research has been based on diverse robotic research platforms differing in their appearance, behavior and intended tasks (Dautenhahn, 2007). Moreover, many research projects have employed diverse methodological measurement techniques and tools, or comprise incompletely described methods (Dautenhahn, 2007). Consequently, a wide range of empirical work can neither be related to each other nor replicated by others (Dautenhahn, 2007), which is particularly reflected in HRP and described more precisely in section 2.7.3.

2.4 Robot Appearance

As a next step, this topic is introduced to permit a classification of the employed robots according to their outward appearance. In addition, it highlights a popular debate in HRI regarding a robot's level of human likeness and corresponding advantages and disadvantages. In regard to a conducted human likeness manipulation of Beam in the third study of this dissertation, it is essential to elucidate the relevance of this topic.

Other than variously emerged robot types, robotic systems differ immensely in their physical appearance, which poses a key feature of a robot (Haring, Watanabe & Mougenot, 2013). In particular, the appearance of a robot evokes human expectations and assessments towards capabilities, functionality or personality of a robot (Lohse, 2007; Haring et al., 2013). However, numerous researchers are continually involved in popular disputes, debating which physical design is the most appropriate for which type of robot, and in addition, how robot appearance and behavior relate to each other (Hinds et al., 2004; Walters et al., 2008a).

In the course of robotic history, two approaches of designing robotic systems have been loomed: biologically inspired and functionally designed (Fong et al., 2003a). Among some more recent literature, this is also referred to as human-oriented design opposed to product-oriented design (Kwak et al., 2014). Human-oriented designs attempt to resemble the appearance of living creatures, those of humans (anthropomorphism) or animals (zoomorphism) (Fong et al., 2003a). Many animal- or human-like robots have been endowed with faces, arms, legs or bodies of their living effigy (Fong et al., 2003a). In contrast, product-oriented design approaches intensely focus on reflecting the robot's task and on maximizing its operational objectives (Fong et al., 2003a; Kwak et al., 2014).

With respect to a robot's human likeness, three diverse terminologies for distinguishable outwardly appearing robots have been established:

1. **Mechanoid** – which is defined by Walters et al. (2008a, p.164) as *'a robot which is relatively machine-like in appearance […] and has no overtly human-like features'*.

2. **Humanoid** - which is defined by Walters et al. (2008a, p.164) as *'a robot which is not realistically human-like in appearance and is readily perceived as a robot by human interactants. However, it will possess some human-like features, which are usually stylized, simplified or cartoon-like versions of the human equivalents, including some or all of the following: a head, facial features, eyes, ears, eyebrows, arms, hands, legs. It may have wheels for locomotion or use legs for walking'*.

3. **Android** - which is defined by Walters et al. (2008a, p.164) as *'a robot which exhibits appearance (and behavior) which is as close to a real human appearance as technically possible. The eventual aim is to create a robot which is perceived as fully human by humans, though currently, humans are fooled for a few seconds under carefully staged circumstances'*.

Examples for all three robot appearances are presented in Figure 2-2 and 2-3.

Figure 2-2 a mechanoid (Nomadic Technologies Inc., 1999)

Figure 2-3 android (left) and humanoid (right) (Macdorman & Ishiguro, 2006)

By employing this defined categorization to the used robots in the present research project, it can be concluded that none of them possess any overtly human-like features and thus, they can be classified as mechanoids. It is important to note that this classification is only valid for the original, machine-like version of Beam. According to Walters et al. (2008a) definition of a humanoid, the human-like version of Beam can be categorized as a humanoid.

The design of humanoids or androids is very popular to date, but whether a humanized appearance of a robot is the most appropriate for a natural and intuitive HRI remains unknown (Hinds et al., 2004, cf. Kwak et al., 2014). By examining effects of a robot's human likeness, many inconclusive findings have been attained (Hinds et al., 2004). For instance, Hinds et al. (2004) confronted a large number of participants with a human-like and machine-like version of the same robot in a collaborative task. Attained findings showed that participants relied more on the human-like robot and shared more responsibility for the task when the human-like robot was used (Hinds et al., 2004). In another study that examined childrens' perceptions and attitudes towards robots, human-like robots were rather judged as aggressive and angry, and machine-like robots were rather rated as friendly and happy (Woods et al., 2004). However, in a similar study, which explored elderly people's attitudes towards robots using a card sorting approach, findings were ambiguous and showed preferences for human-like and machine-like robots, respectively (Wu, Fassert & Rigaud, 2012). In contrast, Li and his colleagues (2010) found that only a zoomorphic robot appearance led to a higher rating of likeability. The presented machine-like and human-like version of a robot did not significantly differ in the attained ratings. As a possible explanation, it was noted that both robot versions, human- and machine-like, exposed mechanical details whereas the animal-like appearance did not expose any of those (Li, Rau & Li, 2010). In a study, surveying requirements for a robot's social acceptance, Oestreicher (2007) found that a machine-like looking robot seems to generate more positive feelings that human- or animal-like robots.

By designing human-oriented robots, developers aspire to better adapt robots to human anatomic preconditions and daily human environments, such as stairs, hallways, elevators (Fong et al., 2003a). Thus, it is not surprising that humanoids also aim to imitate corresponding human behavior (Fong et al., 2003a). Furthermore, assumptions comprise facilitated interactions with humanoids due to an invocation of human social rules (Hinds et al., 2004). By following this approach, humanoids are aspired to meet people's expectations, which in turn leads to a more acceptable and effective HRI (Fong et al., 2003a). However, it is crucial to take either, positive and negative, appearance effects into account while outwardly designing a robotic system.

As already stated in the beginning of this section, external robot appearance affects human expectations. It is even stated that assumptions based on visible robotic features are unconsciously made (Lee, Lau, Kiesler, & Chiu, 2005). In a study run by Powers and Kiesler (2006), it was shown that participants created a plausible mental model of a human-like robot before any interaction with this robot was initiated. Subjects' ratings of the robot's human likeness, knowledge and sociability significantly differed in their scores due to manipulated facial characteristics (chin and forehead size). Subsequently, these diverse perceptions impacted subjects' intentions to obey the robot's advice. Furthermore, given the importance of outward appearance as an interaction modality, which was already suggested by Gibson and his affordance theory (1977), it seems logical that people expect a robot with a mouth or eyes to be capable of talking or seeing (Woods, 2006). On the contrary, a very machine-like robot is not associated with any human-like abilities, and expectations are in general lower compared to human-like robots (Woods, 2006; Walters et al., 2008a). Nonetheless, evoking detrimentally false or misleading expectations result in problematic feelings of disappointment or even fear, or cause unrealistic predictions about the robots future behavior (Dautenhahn, 1999; Hinds et al., 2004; Oestreicher, 2007).

2.5 Uncanny Valley

In this section, a popular hypothesis in robotics – the Uncanny Valley – is introduced. Of particular interest for the present work is the proposed relation of robot appearance and behavior (e.g. motion) to familiarity. In addition, relevant methodological shortcomings and approaches are introduced.

By depicting the high relevance and popularity of exterior robot appearance in HRI, it is ineluctable to come across the Uncanny Valley (Mori, 1970). Published at an early stage in robotic history, this conjecture directly discussed the divergent robotic appearances and their effects on humans (Mori, 1970).

Mori (1970) principally stated that, the more human-like a robotic system appears, the more familiar it is perceived by humans, which peaks at the point of perfect human imitation (cf. Cheetham, Suter & Jäncke, 2011). However, this interplay is non-linear, as proposed by Mori (1970). At a point of relatively high realism, compared to the natural human counterpart, the corresponding level of familiarity drastically collapses – negatively peaking in a repulsive, eerie, very strange, and unsettling feeling – described by Mori (1970) as the Uncanny Valley (cf. MacDorman & Ishiguro, 2006; Dautenhahn, 2007, Cheetham et al., 2011). Within this sector of the chart, objects are perceived as creepy and disgusting despite a high level of human likeness (e.g. zombie, prosthetic hand) (Cheetham et al., 2011; von der Pütten & Krämer, 2012). However, by further increasing the human likeness the Uncanny Valley can be surmounted, reaching the highest familiarity due to a perfect human similarity. In addition, it is vital to note that Mori (1970) plotted familiarity to a further attribute of robots – motion. According to Mori (1970), a robot's motion behavior can either, positively or negatively, intensify the perceived familiarity to the same extent. Mori (1970) reasoned a necessary consistency between appearance and behavior in order to avoid the Uncanny Valley. In general, as proposed by Mori (1970), the Uncanny Valley emerges due to a mismatch of certain robotic attributes (e.g. unrealistic skin covering on a real hand). A simplified and translated version of the graph by Macdorman (2005) is presented in Figure 2-4.

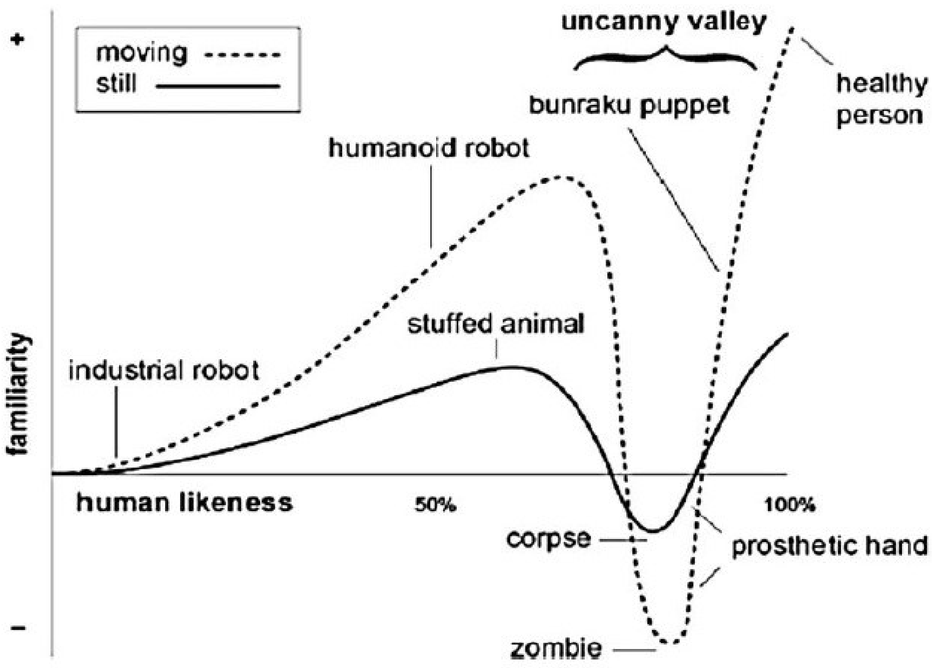

Figure 2-4 the Uncanny Valley illustrated by Macdorman (2005)

Apart from the worst case of evoking the repulsive uncanny valley effect, Mori (1970) proclaimed *'... it is possible to create a safe familiarity with a non-humanlike design'*. Given the machine-like appearance of the employed robots in the present work, this suggestion is of particular interest. However, this predication lacks any specification and demands further exploration. According to Bartneck, Kanda, Ishiguro, and Hagita (2009a), Mori's attempt to model movement as an unidimensional key parameter for the perception of a robot is too simplistic. Again, Mori (1970) has not provided any empirical specifications that explain the potential effects of movement on familiarity in greater detail. Nonetheless, there is some evidence supporting the relevance of robotic motion behavior for people's perceptions towards robots, which is addressed in greater detail in the proximate section.

Altogether, in general, many controversies and debates characterize the Uncanny Valley in existing literature (Bartneck et al., 2009a; Cheetham et al., 2011). To date, most knowledge has been still fragmentary and numerously inconsistent findings exist (Yamamoto, Tanaka, Kobayashi, Kozima & Hashiya, 2009; Cheetham et al., 2011), and therefore, various questions have remained open (MacDorman & Ishiguro, 2006; Zlotowski, Proudfoot & Bartneck, 2013). For instance, Hanson (2006) used two series of morphed images (from a human-like robot face to a real human face) that only differed in the quality of the aesthetic design. He demonstrated that any level of abstraction can be appealing to humans and the uncanny affect can be avoided if the aesthetics are right. Accordingly, with respect to the Uncanny Valley itself, its existence is still equivocal and so are its indicated reasons (MacDorman and Ishiguro, 2006; Pollick, 2010, Zlotowski et al., 2013). By agreeing on an insufficient number of specification, conceptual shortcomings, and divergent or no empirical evidence, the scientific community has primarily rejected the hypothesized phenomenon (Hanson, Olney, Prilliman, Mathews, Zielke, Hammons, Fernandez & Stephanaou, 2005; MacDorman and Ishiguro, 2006; Ho, MacDorman & Pramono, 2008; Zlotowski et al., 2013). Notwithstanding, the myth of the Uncanny Valley has been very influential in serving as a design principle for many roboticists and designers (Ho et al., 2008; Cheetham et al., 2011). At the same time, it is noteworthy to highlight Mori's endeavor to theoretically model certain relations in HRI, even though he has not yet presented any empirically obtained evidence.

In addition, it has been stated in literature by von der Pütten and Krämer (2012) that the proposed concepts of human likeness and familiarity lack precise definitions. As a result, the y-axis dimension has been replaced by a broad range of other constructs, such as acceptance (Mizoguchi, Sato, Takagi, Nakao & Hatamura, 1997; Duffy, 2003; Osawa, Matsuda, Ohmura, 2010), likeability (Bartneck et al., 2009a), affinity (Mori, MacDorman & Kageki, 2012), empathy (Misselhorn, 2009), or even assumed counterpoints to familiarity, like strangeness, eeriness (Ho et al., 2008), or uncanniness (Hanson, 2006; Oehl, Telle, Siebert, Pfister & Höger, 2013). Additionally, in regard to a conducted language evaluation by Bartneck et al. (2009a), no direct equivalent in English for the Japanese terminology employed by Mori (1970) has been found. Likeability has been proposed as a more suitable concept opposed to familiarity (Bartneck et al., 2009a). However, by using such a variety of diverse concepts, many studies lack comparability and thus, cannot be related to each other (Zlotowski et al., 2013).

Further shortcomings comprise the application of non-standardized methodologies (von der Pütten & Krämer, 2012). Many experiments have evaluated human likeness and familiarity, i.e. acceptance, likeability, etc., by using single bi-polar adjective pairs (cf. Macdorman & Ishiguro, 2006; Walters et al., 2008a; von der Pütten & Krämer, 2012). Particularly, a humanoid is often outwardly featured by human-like as well as machine-like attributes, significantly complicating a distinct classification within one bi-polar item (von der Pütten & Krämer, 2012). To measure a certain concept, it is of greater conceptual correctness and benefit, regarding the comparability of diverse experiments, to use standardized measurement tools (Bartneck, Kulić, Croft & Zoghbi, 2009b). Thus, Bartneck et al. (2009b) have elaborated and empirically evaluated several consistent questionnaires comprising semantic differential scales for the concepts of anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety (see Appendix A). Satisfying reliability statistics as well as validity indicators were reported (Bartneck et al., 2009b). As encouraged by Bartneck et al. (2009b), some of their elaborated questionnaires were applied in the third study of this dissertation (see section 5). In particular, the conceptualized questionnaires assessing anthropomorphism, likeability and animacy were employed. According to Bartneck and his colleagues (2009b, p.74), *'Anthropomorphism refers to the attribution of a human form, human characteristics, or human behavior to nonhuman things such as robots, computers, and animals`*. Thus, this questionnaire assesses the human likeness of a robot. The second questionnaire (likeability) aims to assess positive impressions towards the visual appearance or behavior of a robot (Bartneck et al., 2009b, p.75). In addition, according to Bartneck et al. (2009b, p.74), a robot's animacy referes to the classic perception of life and thus, measures how lifelike a robot seems to be.

In line with measurement tool deficits, experimental material (for instance a humanoid) has often been inconsistently presented across different studies that additionally complicated their comparability (Pütten & Krämer, 2012).

Beyond methodological issues, Mori's (1970) chart neither considered cultural differences, general attitudes, preferences or familiarity towards technology, nor inter-individual differences, which affect the perception of robots (Bartneck, Kanda, Ishiguro & Hagita, 2007; Bartneck et al., 2009b; Lee & Sabanović, 2014)

2.6 Relevance of Robotic Motion Behavior

In this section, it is aimed to expound the prevailing state of knowledge regarding Mori's (1970) suggested relation of appearance and motion behavior, and additionally, the relevance of robotic motion behavior for familiarity, i.e. people's perceptions towards robots. Especially, the diagram's left hand side and corresponding empirical findings pose a meaningful input for the developed hypotheses, regarding the manipulated level of human likeness and its effects on participants' sensations and distance preferences, in the third study of this dissertation.

According to the Uncanny Valley chart (Mori, 1970), though its right hand side is controversial, mechanical-looking and human-like robots were assigned by Mori (1970) to the rather proven left hand side of the graph (Zlotowski et al., 2013). Based on the given definitions of diversely appearing robots by Walters (2008), the employed machine-like looking robots of the present work can be placed in the initial section of the graph, around the indicated industrial robot. If Beam is more human-like than the transport assistant remains open at this point. Potentially, Beam's appearance is rather associated with the anatomy of a human through its height and leg-like properties of the sticks Beam's screen is mounted on. Additionally, the human-like version of Beam can be placed nearby the indicated humanoid robot, which is illustrated in Figure 2-5.

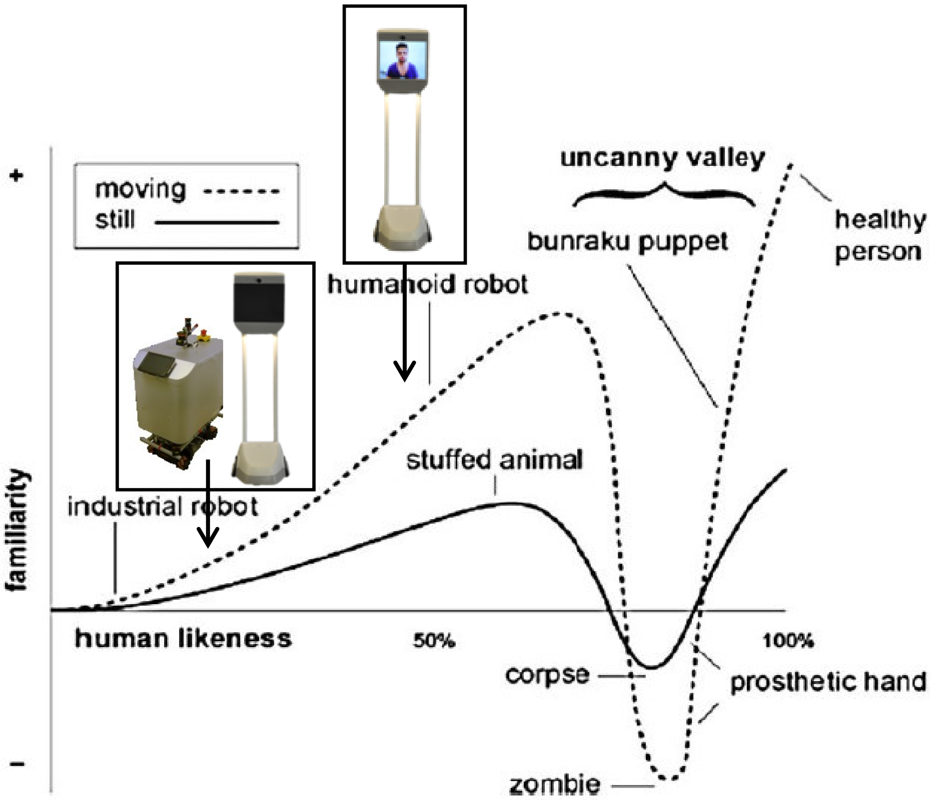

Figure 2-5 assignment of applied research platforms to the Uncanny Valley chart

Originally, Mori (1970) proclaimed the necessity of a prevailing consistency between robotic appearance and motion behavior in order to avoid a mismatch, which in turn provokes strongly negative sensations for humans. As already mentioned, physical designs evoke divergent behavioral expectations which are crucial to prove true in order to prevent feelings of surprise, disappointment, disturbance, or even fear (Hinds et al., 2004; Oestreicher, 2007; Bartneck et al., 2009b). However, in regard to a mechanical-looking robot, Mori (1970) claimed that by designing more humanlike movements, the perceived sense of familiarity would increase. In particular, he stated that the design of more human-like movements encloses the implementation of similar levels of single motion attributes as observed in HHI, such as speed or acceleration. In addition, Billiard (2005) postulated that robotic kinematics should align to major human movement characteristics. It is relevant to conclude at this point that Mori's (1970) proposed consistency rather refers to general types of motion in relation to a robot's appearance, for instance a human-like robot with human legs and feet is expected to walk like a human instead of moving on wheels. However, more detailed motion features, such as speed or personal space, can be beneficial for a machine-like robot's familiarity if they align to human motion attributes (Mori, 1970; Billiard, 2005). In line with Mori (1970), numerous other researchers have postulated the described potential of robotic motion behavior on people's perceptions (Dautenhahn, 2002;

Minato, Shimada, Ishiguro & Itakura, 2004; Forlizzi, 2007; Walters et al., 2008a). In addition to Mori's (1970) premise regarding a consistent match of robot appearance and behavior, Goetz, Kiesler & Powers (2003) stated that robotic behavior and appearance should be matched to the type of task context in order to meet people's expectations. Based on an experiment, involving varied robot behavior (playful/serious) and varied appearance (machine-like/human-like), participants cooperated more with a machinelike and seriously behaving robot in a serious task context, and vice versa (Goetz et al, 2003). Accordingly, it has been proposed by Goetz and his colleagues (2003) that a human-like robot design does not always lead to improved impressions.

With respect to Mori's (1970) suggested relevance of robotic motion behavior, numerous studies can be reported that have provided evidence in the HRI context.

In a study run by Nakata, Sato, Mori and Mizoguchi (1998), a robotic pet showed diverse head movements (up/down/nothing) when it was touched. Attained findings demonstrated that participants perceived both head moving scenarios as more familiar than the control condition (no head movement), which produced bad impressions. In a follow-up experiment, the same authors presented a diversely dancing humanoid to 10 participants, and subsequently assessed their emotions by applying questionnaires. It was shown that only a change in the robot's movement evoked various emotions, such as joy, anger or sadness.

By investigating people's willingness to engage in an interaction with a mobile robot, Bruce, Nourbakhsh and Simmons (2002) found that a robot's ability to show attention by turning towards the participant rather attracted participants' attentiveness.

Furthermore, it has been shown that motion behavior alone was found to evoke an increased perception of human likeness (Shick, Forlizzi & Fussell). By setting up an obstacle course for a vacuum robot and three diverse motion patterns, participants' understanding and perception of the motion behavior was evaluated. The applied motion patterns involved different error levels regarding the robot's objective to reach the other end of the course. Findings revealed that the robot which made the least mistakes was either, understood and anthropomorphized, the most (Shick et al.). Thus, the motion behavior alone led to a higher perception of human likeness. It was suggested that participants could rather detect a recognizable pattern and predict the robot's goal in the condition comprising least mistakes. Instead, participants were confused and kept trying to detect a pattern in the other conditions, comprising more mistakes.

The same effect was also found in a study by Walters et al. (2008a). Their goal was to address Mori's (1970) assumed interplay of the diagram's left hand side. Walters and his colleagues (2008a) exposed the participants to pictures and videos that showed the same robot (PeopleBot) with three outward designs, ranging from mechanical-looking to human-looking. Apart from a changed static design in pictures, design alterations in videos also involved further robotic features, such as more human-like arm movements or voice styles. Upon each presentation, participants were instructed to rate the perceived level of human likeness on a simple bi-polar scale. Attained findings showed higher ratings for more human-looking versions of the robot. Importantly, human likeness ratings of the same robot design were higher when presented in a video than in a picture. Hence, this study supported Mori's idea that robot behavior plays a crucial role in affecting humans' perceptions of robots (Walters et al., 2008a). However, the study could have been potentially biased due to a conducted labeling of the exposed robots according to their appearance (mechanoid, humanoid) (Walters et al., 2008a).

In another study, a humanoid's cooperative behavior in a common task with a human was designed more human-like by adapting arm and head movements to a usual human behavior in a comparable context (Kanda, Kamasima, Imai, Ono, Sakamoto, Ishiguro & Anzai, 2007). The design manipulation evoked that the humanoid pretended to listen to participants and attained results demonstrated increased perceptions of the robot's reliability and sympathy.

In accordance with previously presented findings, research has also shown that a machine-like looking rescue robot, which was perceived as creepy by trapped people, was perceived as less threatening due to the use of more appropriate body movements and postures (Bethel & Murphy, 2006).

In addition, a wide range of studies in the field of human-robot spatial interaction (HRSI) has presented evidence for Mori's proposed effects of robotic motion behavior on people's perceptions and attitudes towards robots (e.g. Butler & Agah, 2001; Walters, Dautenhahn, Woods, Koay, Te Boekhorst & Lee, 2006; Pacchierotti et al., 2006; Mumm & Mutlu, 2008; Takayama & Pantofaru, 2009; Brandl, Mertens, Blotenberg, Lüdtke, Jacobs, Bröhl, Mayer & Schlick, 2013). Within all these experiments, it was shown that robotic motion behavior, considering human spatial conventions (e.g. personal space), led to higher levels of comfort for participants. These findings are more precisely expounded in section 2.7.3.

Altogether, it can be stated that motion behavior is of particular significance regarding an acceptable integration of robotic technology into shared spaces with humans (Brooks & Arkin, 2007). Furthermore, forms of non-verbal communication, such as motion behavior, have been posit by previous researchers as an alternative to work around technological challenges, such as speech recognition and production (Mizoguchi et al., 1997).

Nonetheless, as already highlighted in section 2.3, robots are not people and it is unlikely that humans expect the same social reactions from robots as from humans in comparable contexts (Friedman et al., 2003; Dautenhahn, 2007; Takayama & Pantofaru, 2009; Sardar et al., 2012). Presented research has uncovered that social paradigms and conventions, known from HHI, play a relevant role in HRI as well. However, human behavior cannot be simply copied (Gockley, Forlizzi, & Simmons, 2007).

Thus, caution needs to be taken when adapting robotic motion behavior to machine-like looking robots for incorporating social skills on one hand, and avoiding an evocation of false expectations on the other (Walters, 2008). Essentially, it is proclaimed in robotic literature by Daffy (2003, p. 181), that *'anthropomorphism should not be seen as the "solution" to all human-machine interaction problems but rather it needs to be researched more to provide the "language" of interaction between man and machine'*. As stated by Gockley et al. (2007), it is vital to match robotic behavior to human expectations, whereat it is in general unknown whether, for instance, people expect a mechanoid to move at the exact same walking speed as humans. Thus, to what extent a socially deployed mechanoid should adhere its motion behavior to underlying human principles has posed a key question to date. This issue is well-reflected in the central field of this dissertation – human-robot spatial interaction (HRSI) – and is therefore elucidated in greater detail in the succeeding sections.

2.7 Human-Robot Spatial Interaction

This section introduces the relevant HRI sub-domain, which precisely addresses robotic motion behavior – HRSI – and provides an overall understanding of the field and its relevance for the present work.

As shown in the previous section, robotic motion behavior is of high relevance for people's perceptions towards social robots. Importantly, robotic motion behavior poses the central subject of the HRI sub-domain – human-robot spatial interaction (HRSI) - which 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'* (Bellotto et al., 2013, p.331).

By considering the physical constitution of a mechanoid, which is moving on wheels instead of possessing human-like legs, a socially adequate HRSI is of paramount importance for contributing to an overall socially accepted HRI (Lichtenthäler, Peters, Griffiths & Kirsch, 2013). A HRSI involves several aspects of robotic motion features, such as robot speed, distance behavior, spatial prompting, or body orientation (Butler & Agah, 2001; Peters, 2012).

With respect to the overarching problem of the present work, a particularly interesting feature of HRSI is the robot's distance behavior. Due to the physical embodiment of robotic systems, robots constantly produce social spaces, similar to humans (Lindner & Eschenbach, 2011). In order to meet people's expectations, social robots are required to consider their own and humans' social spaces, and the corresponding social meaning (Lindner & Eschenbach, 2011). The corresponding science, studying personal and interpersonal spaces of humans, is called proxemics (Hall, 1966), which has been intensively explored in HHI. Accordingly, the study of personal and interpersonal space poses a key feature in HRSI as well (Walters, 2008; Mutlu & Forlizzi, 2008; Kirby, 2010; Lindner & Eschenbach, 2011; Peters, 2012). It is labeled human-robot proxemics (HRP) (Walters, 2008) and both, human-human proxemics (HHP) and HRP, are expounded in greater detail in the succeeding sections.

Previous research has already revealed that a social service robot is in essential demand of socially appropriate distance behavior for acceptably sharing the living space with humans (Mutlu & Forlizzi, 2008). Establishing a comfortably indirect interaction through motion, as seen in human-human interaction, poses a required new dimension of robotic motion behavior aside from safe navigation (Butler & Agah, 2001; Peters, Weiss & Hanheide, 2009; Kirby, 2010). Importantly, a comfortable motion behavior can be distinguished from a safe one. Kruse, Pandey, Alami and Kirsch (2013) pointed out that comfort *'is the absence of annoyance and stress for humans in interaction with robots'* and that *'even when a robot is moving safely, an observer may still feel that the motion is not safe, lacking trust in the technology'* (Kruse et al., 2013, p.1728).

In a long-term study evaluating the performance of a machinelike-looking transport robot (Aethon TUG) in hospitals, Mutlu and Forlizzi (2008) found that people disliked and were even annoyed by the robot due to blocking the way, approaching people inappropriately close or even colliding with people. By interviewing and observing all kinds of people in the hospitals, it was shown that the robot's inappropriate spatial behavior impaired the overall workflow. Furthermore, people reported to feel disrespected by the robot and desired a robot with more manners. Accordingly, the examiners and other researchers proposed that a coexistence with humans requires a social robot to respect social spaces and demands a spatial behavior in a way that meets people's expectations (Mutlu & Forlizzi, 2008; Lichtenthäler et al., 2013). It has been further postulated that the design of appropriate social spatial behavior increases the overall social acceptance by increasing the predictability and legibility of robotic motion behavior (Lichtenthäler et al., 2013), which in turn supports a societal integration of this sort of robot (Pacchierotti et al., 2006; Takayama & Pantofaru, 2009; Mumm & Mutlu, 2011). A wide range of other studies, more precisely addressing the field of human-robot proxemics, has been revealing the relevance of a socially adequate distance behavior of a robot. They are introduced and discussed in greater detail in section 2.7.3.

Regardless of the noted relevance of a socially appropriate designed HRSI, research in HRI has been rather focused on other fields, such as physical design (Hinds et al., 2004; Ishiguro, 2007), multimodality (Al Moubayed, Beskow, Bollepalli, Gustafson, Hussen-Abdelaziz, Johansson, ... & Varol, 2014), haptics (Aydin, Arghavani & Basdogan, 2014), speech (Miyanaga, Takahashi & Xihao, 2013), brain-computer interfaces (Huang &

Ramirez-Serrano, 2014), gaze behavior (Mutlu, 2008), or on intuitive control of flying robots (Blum, Berthold, Rhan & Hafner, 2014). For instance, in August 2014 (time of retrieval), the term *'uncanny valley'* led to 34000 search results opposed to barely 700 results for *'human-robot proxemics'* at Google Scholar (Google Scholar, 2014). Accordingly, in relation to other fields, a robot's spatial behavior has rarely been addressed and systematically explored yet (Woods et al., 2004; Brooks & Arkin, 2007; Mumm & Mutlu, 2011). This is very surprising since several features of human motion behavior, such as personal space, walking speed, or body orientation have been intensively explored and pose a crucial part of human non-verbal everyday communication (Knapp, 1972; Spiegel & Machotka, 1974; Bull, 1987; Bartneck, 2002). It is even stated by Spiegel and Machotka (1974), and by Bull (1987), that motion behavior can reflect the current state of a person to a greater extent than verbal communication.

The imbalanced research attention in HRI is also reflected in available human-aware navigation frameworks. It has been stated that many implemented navigational algorithms for robots have not considered any known spatial human norms yet (Kirby, 2010). Others have simply attempted to imitate human behavior regardless of people's expectations, which often resulted in rather unnatural motion patterns due to sudden safety activations, inopportune implementation, or challenges of modeling human behavior (Bellotto et al., 2013). Moreover, Lichtenthäler, Lorenzy and Kirsch (2012) recently stated that the quality of common navigation methods, with respect to legibility and perceived safety, is rather low.

2.7.1 Human-Human Proxemics

As mentioned in the previous section, proxemics constitutes a key feature in daily human interactions and has been intensively studied. This section introduces the relevant theoretical background of this discipline, corresponding empirical findings and methodological approaches in human-human proxemics (HHP) research.

Already more than 60 years ago the striking importance of non-verbal communication, such as body movements, gaze and postures has been published (Birdwhistell, 1952). In the following years, aspects of non-verbal communication have been progressively investigated (e.g. Knapp, 1972; Spiegel & Machotka, 1974; Argyle, 1975), and their relevance has been also revealed by the widespread axiom from Watzlawick (2011, p. 15) *'one cannot not communicate'*. Facets of motion behavior, such as gestures or personal space, have been argued to convey fundamental information for carrying out interactions as well as structure them meaningfully (Ogden & Dautenhahn, 2000). All aspects of motion behavior belong to the discipline of kinesics, which was founded by the anthropologist Ray Birdwhistell (1952, p.3) and defined by him as *'aspects of the study of body motion as related to the non-verbal aspects of interpersonal communication'*. Taken together, he was the first who proposed the vital social meaning of motion behavior. According to Brinker, Antos, Heinemann and Sager (2000), kinesics can be subdivided into motor activity (e.g. mimics, gestures), gaze and haptics, and proxemics, which has been seen as a subcategory of locomotion. Thus, proxemics poses a significant attribute of human motion behavior and according to Hall (1973, p.180) *'spatial changes give a tone to a communication, accent it, and at times even override the spoken word'*.

In fact, humans possess the remarkable capability of coordinating and optimizing their space in a non-verbal and non-random way, which can be observed in everyday life (Bennewitz, 2004; Weiss et al., 2011). In general, humans can fairly well predict mutual trajectories and avoid bumping in to each other without exchanging a single word (Frith & Frith, 2006; Crick et al., 2007). Apparently, human spatial coordination follows underlying social rules, an invisible structure of pivotal importance for conveying intentions, which leads to coordination and comfort in human-human spatial interaction (Goffmann, 1983). The corresponding scientific discipline, addressing the social use of space and interpersonal distance, is called proxemics (Hall, 1966). As a pioneer, who widely studied this field, Hall (1966) provided a systematic basic for physical and psychological distancing from others (Breazeal, 2004; Mumm & Mutlu, 2011). Proxemics poses a central social convention, including relative positioning and orientation of interacting agents (Ogden & Dautenhahn, 2000). As previously noted, proxemics plays a key role in everyday human-human interaction, which is reflected in numerous situations, such as people withdraw when someone approaches them inappropriately closely, drivers can be really annoyed by being *'tailgaited'*, people install fences around their property, or playing in their own stadium is seen as advantageous for most sport teams (Hall, 1966; Sommer, 2002a). These are just some examples among many others, well-reflecting the social meaning of space.

The roots of human spatial behavior can be traced back to our ancient ancestors and animals (Hall, 1966). Surprisingly, the spatial behavior of animals has been more intensively explored by ecologists than human spatial behavior by anthropologists and psychologists (Sommer, 2002a), who mainly investigated this field before 1983 (Uzzell & Horne, 2006). It has been well explored that animals have territories which they defend against each other, and supplementary, uniform distances which they maintain around each other (Hall, 1966). In particular, Hediger (1950) classified these distances in flight, critical, personal and social. The flight distance serves a vital protection mechanism against predators. The critical distance constitutes the required minimum space to survive and simultaneously protects against overexploitation (Hall, 1966). Personal and social distances shape interactions among them and surround each animal like an invisible bubble (Hall, 1966).

However, in the course of human history, people have set themselves apart from nature, and in most cases, lost their flight and critical distance by domesticating themselves (Hall, 1966). Nonetheless, as already noted, humans still possess a personal and social space, and personal space was defined by Sommer (1969, p.26) as *'an area with invisible boundaries surrounding a person's body into which intruders may not come'*. It is noteworthy to mention that personal space cannot be equaled with the concept of a stationary and marked territory (Hayduk, 1978). Personal space rather poses a portable territory around the human body with invisible boundaries and intrusions lead to compensatory behavior, such as withdrawal, attempting to readjust a comfortable spatial relationship (Sundstrom & Altman, 1976; Hayduk, 1978). In contrast, the stationary territory has no fixed center and intrusions lead to flight and threat reactions (Hayduk, 1978).

Furthermore, due to our artificially shaped environment, personal space can disappear under certain conditions (e.g. crowding) and people also accept inevitable invasions in their personal space (Sommer, 2002a). According to Hall (1966), humans' sense of space is a function of emotion, activity, relationship and culture, perceived by a synthesis of visual, auditory, olfactory, kinesthetic and thermal stimuli. Though maintaining social spaces substantially mediates relationships among interactants, conveys information of emotional states, attitudes or motives (Harrigan, Rosenthal & Scherer, 2005; Marquardt & Greenberg, 2012), Hall (1966) assumed that proxemics is a silent language, which is acquired during an early stage in life (Aiello & Aiello, 1974; Sommer, 2002a).

However, proxemics has been widely postulated as a crucial automatic mechanism in human environments to avoid discomfort, misunderstanding or stress (Watson, 1970; Sundstrom & Altman, 1976; Hayduk, 1978; Hayduk, 1983). Recent research has corroborated these prominent emotional reactions towards personal space violations. Kennedy, Gläscher, Tyszka and Adolphs (2009) investigated personal space violations in relation to subjects with complete amygdala lesions and found that these persons lacked any sense of personal space. In contrast, healthy subjects showed strong amygdala activations, which indicated the essential emotional meaning of personal space since the amygdala has been found to play a key role for human emotion, social cognition and social behavior (Phelps & LeDoux, 2005; Kennedy et al., 2009)

But what are the underlying psychological reasons for this phenomenon?

While Hall's research rather focused on exploring the structure of personal space, succeeding research has developed diverse theories, addressing potential reasons for negatively aroused feelings upon personal space violations. An excellent overview has been provided in papers by Hayduk (1978, 1983). Altogether, four diverse theories have been suggested:

1. *The Argyle-Dean Intimicy Equilibrium Theory (Argyle & Dean, 1965)*
2. *The Duke-Nowicki Social Learning Theory (Duke & Nowicki, 1972)*
3. *The Dosey-Meysels Protection Theory (Dosey & Meisels, 1969)*
4. *The Nesbitt-Steven Stimulation Theory (Nesbitt & Steven, 1974)*

The *Argyle-Dean Intimicy Equilibrium Theory* assumes that each person desires a certain level of intimacy. All in all, they have proposed that the overall level of intimacy is a joint function of eye contact, interpersonal distance, smiling intensity, intimacy of topics discussed and other factors (Argyle & Dean, 1965; Hayduk, 1978). If one dimension becomes too intense and leads to discomfort, a compensation can be made by decreasing the level of a different dimension in order to restore the desired comfortable level of intimacy (Patterson, Mullens & Romano, 1971).

In one experiment, Argyle and Dean (1965) requested participants to place themselves in a comfortable distance in front of a confederate who constantly gazed at the subjects or shut his eyes. Findings revealed that participants stand closer to the confederate when his eyes were shut (~0.86m) than open (~1.1m). The distance between the persons' eyes was measured by employing a ruler. Thus, Argyle and Dean (1965) found that an increased proximity led to a decreased level of eye contact. However, further empirical studies have revealed consistent and inconsistent findings.

Baxter, Rozelle and Richard (1975) confronted subjects with a simulated police investigative face-to-face interview and observed their non-verbal behavior while manipulating the interpersonal crowding. It was observed that subjects significantly decreased eye contact when interpersonal distances were increased. In line with this finding, Goldberg, Kiesler and Collins (1969) observed that participants who sat closer to the examiner established significantly less eye contact.

However, in an experiment, which took place in a library (Patterson et al., 1971), the examiner diversely invaded the personal space of sitting participants and findings revealed that compensatory reactions comprised leaning away and blocking reactions, instead of the suggested dimensions by Argyle & Dean (1965). In addition, Mahoney (1974) investigated whether presumed dimensions of compensatory behavior already exist before invasion scenarios and are thus, rather normal random behaviors. His observation in a library revealed support for his hypotheses, showing that presumed compensatory behaviors are not exclusively linked to a moderation of intimacy.

The *Duke-Nowicki Social Learning Theory* suggests that interpersonal distance is dependent on available expectancies which is related to the social learning theory by Rotter, Chance and Phares (1972). If no expectancies are available due to a stranger, the locus-of-control is lower, which in turn leads to increased distances. This locus-of-control is an integral part of the social learning theory and has been proposed by Doke and

Nowicki (1972) to mediate interpersonal distances. However, according to Hayduk (1978), this theory has been largely untested and the experiment of Duke and Nowicki (1972) was based on a rather non-reliable and invalid paper-pencil approach, asking participants to imagine and indicate their desired distances on a diagram, comprising eight emanating circles from a central point. According to Hayduk (1978), this theory rather poses a minor variant of the *Dosey-Meisels Protection Theory*, which is introduced in the succeeding paragraph. In the following years the expectancy theory evolved from the social learning theory, suggesting that the characteristics of the other person and the situational norm determine the resulting interpersonal distance (Hayduk, 1983). However, in line with the *Duke-Nowicki Social Learning Theory,* existing evidence has shown problems (Hayduk, 1983). Though the theoretical concepts hold true for expectancy confirmations (reward) or violations (punishment), no support was found for a neutral other person (Burgoon, 1978).

The *Dosey-Meisels Protection Theory* proposes that personal space is a dependent variable of the perceived threat and is therefore used for protective purposes (Hayduk, 1978). Perceived threat can be divided into potential threat towards our self-esteem or towards bodily harm (Hayduk, 1978). Dosey and Meisels (1969) found that subjects' level of stress significantly increased the closer they approached each other. Therefore, they concluded that greater perceived threats cause larger interpersonal distances (Hayduk, 1978). However, it has been highlighted that for a particular level of threat exists a threshold value for distance, meaning that distances equal or greater than that threshold should not cause discomfort or dissatisfaction (Hayduk, 1978). In contrast, an overshooting of that threshold distance presumably leads to compensatory behavior, such as withdrawal (Hayduk, 1978).

In relation to all other theories, the *Dosey-Meisels Protection Theory* has received the most support to date (Altman, 1975; Hayduk, 1978; Sommer, 2002a; Lloyd, 2009). Some minor variants of this theory have been also proposed, such as the already mentioned *Duke-Nowicki Social Learning Theory* or a theory by Evans and Howard (1973), suggesting that personal space controls acceptable stress levels and intraspecies aggressions. For instance, Dabbs, Fuller and Carr (1973) investigated comfortable conversation distances and found that subjects maintained greater distances from each other when they were approached by others opposed to when they approached others.

In another study, neuropsychiatric patients were treated with diverse assertion training programs to decrease their level of anxiety (Booraem & Flowers, 1972). Personal space was measured as a dependent variable and findings revealed that a decreased level of anxiety led to a smaller personal space. In a more recent study, investigating neural mechanisms in threating social interactions, subjects were threatened by a virtual predator (Mobbs, Petrovic, Marchant, Hassabis, Weiskopf, Seymour, ... & Frith, 2007). As the predator got closer, neural activity was found in a region, which is identified in rats to facilitate escape behavior in response to threat (Mobbs et al., 2007; cf. Lloyd, 2009). Taken together, no counter evidence has been found for this theory to date.

Lastly, the *Nesbitt-Steven Stimulation Theory* refers to a central statement from Hall (1966), describing that people perceive each other more intense at closer distances. The visual, thermal and olfactory sensory input is largely increased, which causes high levels of stress and aversion (Nesbitt & Steven, 1974; Hayduk, 1978). Appropriate distance adjustments aid to moderate this high level of stimulation, according to Nesbitt and Steven (1974). In two studies, the authors observed people standing in line in an amusement park. It was found that persons in line stood further away from the person in front of them when this person wore very colorful clothes or used perfum compared to persons with less colorful clother and no scent. However, no further support for this theory has been found in literature (Hayduk, 1978).

Another crucial aspect for the present work is the shape of a person's personal space. According to Hayduk (1978), the precise shape of personal space was rarely investigated during the initial years of proxemics research, but received greater attention in the early 80's (Hayduk, 1983). In general, it has been assumed that personal space comprised three dimensions as illustrated in Figure 2-6.

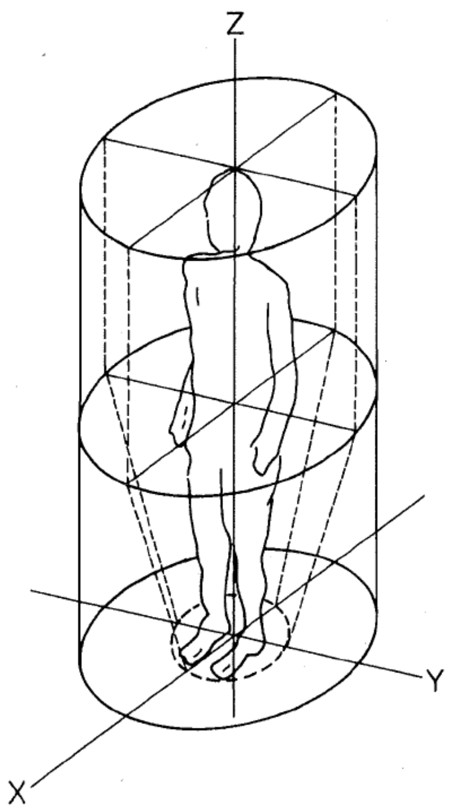

Figure 2-6 dimensions of personal space (Hayduk, 1978)

In addition, several researches, including Hall himself (1966), have presumed that personal space is highly dynamic in its size and does not equally extent in all directions (Ashton & Shaw, 1980; Sommer, 2002a). In an early study, even before the interest in personal space had developed strongly, McBride, King, and James (1965) tried to investigate an effect which they had observed between chickens. Subjects were seated in a chair and were approached by another person from different orientations. As a dependent variable, the Galvanic Skin Response (GSR) was measured. Results indicated that the GSR was greatest when subjects were frontally approached and the GSR diminished for all non-frontal approaches, suggesting that personal space might be less sensitive/smaller for lateral or rear zones. Ashton & Shaw (1980) directly addressed this subject by instructing subjects to walk towards another person and stop as soon as they started to feel uncomfortable. Importantly, the approach direction was varied, resulting in frontal, lateral and rear approaches. Results indicated that frontal mean distances were greater than lateral and rear mean distances (frontal: 0.46m, lateral: 0.34m, rear: 0.32m).

A further evidence for the non-circularity of personal space has been provided by Hayduk (1981). In his study, he placed subjects in the center of a room and approached them from eight different directions, covering frontal, lateral and rear approaches. Subjects were instructed to say stop when the approaching examiner reached an uncomfortable distances towards them and the resulting distance was then measured. A further experimental variation comprised the restriction or permission of subjects' body and head orientation. In some trials, participants could turn their eyes, head or body as they wished, but in other trials, subjects were instructed to constantly face one direction with their head or body. Importantly, the examiner attempted to keep his walking speed and gaze behavior (facing subjects' necks) consistently.

In sum, findings revealed that personal space dimensions almost regularly declined from a maximum frontal (~0.59m) to a minimum rear distance (~0.03m). Interestingly, this minimum rear distance occurred when subjects had to keep their head directed forward. In general, all accepted approach distances were larger when subjects could turn their head and therefore see the approaching person. Accordingly, these findings have suggested that acceptable approach distances are related to the subjects' head orientation (Hayduk, 1981). Unfortunately, no further specific investigations have addressed this topic (Hayduk, 1981).

In accordance with these empirical indications, several researchers have posit an egg form around a person that is greater in front of a human compared to lateral and rear areas (Goffmann, 1971; Ashton & Shaw, 1980; Hayduk, 1981; Hayduk, 1983; Shozo, 1990; Barney, 2003; Amaoka, Laga & Nakajima, 2009).

Nonetheless, the body of knowledge regarding the shape of personal space remains rather vague compared to its intensively explored frontal zone structure. It is striking that most research in HHP has focused on exploring frontal distance preferences. Hall (1966) elaborated an initial notation system, classifying frontal spatial distances among people into four different zones (intimate, personal, social, public). Hall (1966) primarily assumed that interpersonal distances are associated with shifts in the loudness of our voice. Thus, his experimental approach involved a pilot test in which he talked to an associate at various distances. Each time when they agreed on a shift in the loudness of his voice, they measured the corresponding distance. Subsequently, Hall (1966) evaluated this distances with subjects from North America by using the same method. He further sub-divided each zone into a far and close phase, which is subsequently introduced:

1. *Intimate zone (from 0 to 0.46m)*
    a. *Close intimate zone* – whispering, wrestling, love-making, comforting, protecting, physical contact, very close relationships

b. *Far intimate zone* – hands can reach, low level voice

2. *Personal zone (from 0.46m to 1.22m)*
    a. *Close personal zone* – moderate voice level, touching other person is possible, close relationships
    b. *Far personal zone* – moderate voice level, keeping someone at arm length, just outside easy touching distance, people have personal interest in each other

3. *Social zone (from 1.22m to 3.6m)*
    a. *Close social zone* – normal voice level, no touching, impersonal business relationships
    b. *Far social zone* – louder voice level, more formal character of business or social talks

4. *Public zone (apart from 3.6m)*
    a. *Close public zone* – loud voice, subliminal form of flight distance
    b. *Far public zone* – loud voice, distance kept from public figures

Taken together, Hall's (1966) initial notation system and the suggested shape of personal space has been well-illustrated by Amaoka et al. (2009), which is shown in Figure 2-7.

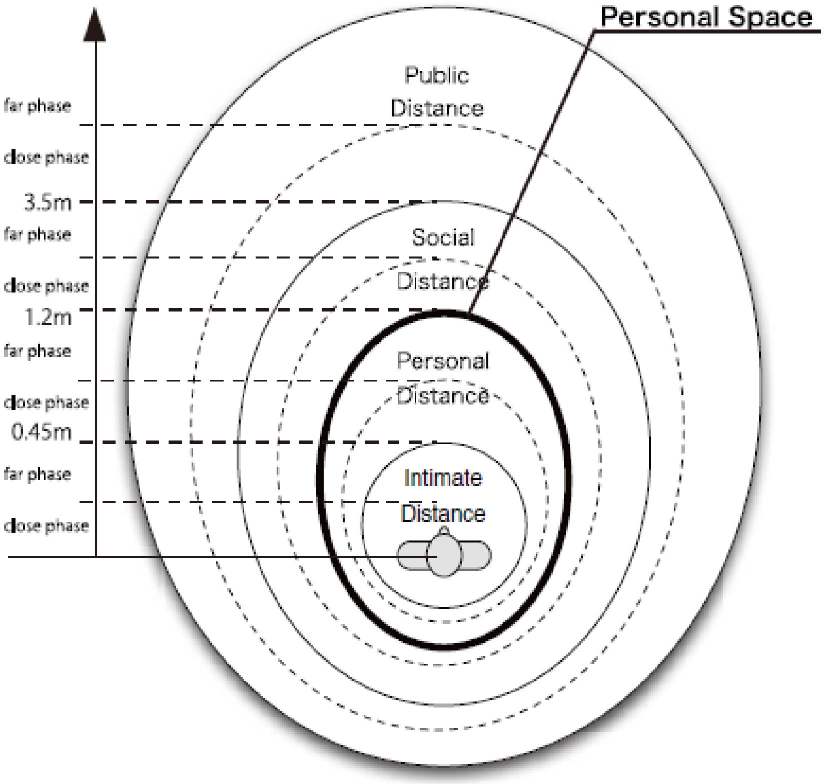

Figure 2-7 illustration of the presumed personal space shape (Amaoka et al., 2009)

In regard to assessing the size of personal space, the following measurement methods have been reported as the most common ones in HHP (Hayduk, 1978).

1. *Stop-distance technique*
2. *Chair placement and selection technique*
3. *Paper-and-pencil or felt board technique*
4. *Unobtrusive techniques*

The *stop distance technique* has been by far reported to be most the reliable and thus, the most preferable procedure (Hayduk, 1978). It was introduced by Kinzel (1970) and includes a subject which approaches another person or is approached by another person until a threshold of comfort is reached (Hayduk, 1978). The resulting distance is then measured (Hayduk, 1978). By permitting to readjust the distance or to repeat a trial, measurement error can be minimized (Hayduk, 1978). Furthermore, Hayduk (1978) pointed out that it is important to approach or be approached at a constant speed. Though this method is obtrusive, personal space only shrank about 8% compared to unobtrusive methods (Hayduk, 1978). However, this method has been widely reported as very feasible and the most reliable approach (Hayduk, 1978; Sommer, 2002a).

Nonetheless, several studies have obtained diverse frontal approach mean distances. By instructing subjects to walk towards a standing person and stop at a comfortable distance, Stratton, Tekippe and Flick (1973) reported a comfortable frontal approach mean distance of approximately 0.51m. In a study comprising the same instruction, a grand mean of 0.65m was observed (Gifford, 1983). Horowitz, Duff & Stratton 1964 instructed participants to actively stop as soon as they started to feel uncomfortable while frontally approaching another person. Obtained results revealed an average frontal approach distance of 0.21m. In contrast, as previously reported, Hayduk (1981) observed an average frontal approach distance of 0.59m upon instructing participants to say stop as soon as they started to feel uncomfortable. This large variance of diverse frontal approach distances has primarily emerged due to a rich body of influencing factors on interpersonal distance and a lack of methodological comparibility and accuracy. In addition, Hayduk (1983) noted that there are large individual differences in the size of personal space and people's degree of reactions to invasions can largely differ. In average, people start to feel slightly uncomfortable at around 0.7m and this feeling proportionally increases with each decimeter, reaching a strong feeling of discomfort at around 0.3m (Hayduk, 1983). However, the large individual differences can lead to smaller or larger distances (Hayduk, 1983). Thus, it is important to assess mean thresholds of comfort.

The *chair placement and selection technique* typically involves an observation of participants adjusting a seating distance towards a confederate (e.g. Barrios, Corbitt, Estes & Topping, 1976), or of participants who already sit somewhere and are intruded by another person adjusting a seating position towards or around the subjects (e.g. Mahoney, 1974; Fisher & Byrne, 1975). According to Hayduk (1978), this method incorporates several disadvantages and its precise relation to personal space is rather unknown. The visible boundaries of a chair and posture effects might be confounded with personal space (Hayduk, 1978). In addition, this method does not permit spatial readjustments as the *stop-distance technique,* but permits stable distance assessments (Hayduk, 1978).

The *paper-and-pencil or felt board technique* has in common that subjects have to imagine their desired interpersonal distance or personal space. Felt board approaches are based on figures which should be arranged on a board to each other (Hayduk, 1978).

Subjects are instructed to place their self-referent silhouette in a spatial relation to other figures on the board (Guardo & Meisels, 1971). Paper-and-pencil approaches request participants to mark the desired interfigure distance on a paper or diagram (e.g. Duke and Nowicki, 1972). In sum, these two methods heavily rely on subjects' cognitive abilities and are therefore less appropriate. By exclusively imagining the situation, important aspects of our spatial perception can be lost (physical setting, characteristics of the other person, sensory inputs) (Hayduk, 1978). In addition, subjects are confronted with an unusual perspective and different distance dimensions compared to reality (Hayduk, 1978). In sum, lower and more variable test-retest reliabilities have been found for these projective measures compared to the *stop-distance technique* (Hayduk, 1983). In an interesting study, Love and Aiello (1980) put subjects in a conversation scenario and measured their real interpersonal distances. Subsequently, they asked the subjects to replicate their actual spacing by using *felt board and paper-and-pencil techniques* and found that the projective measurement approach was even negatively correlated with the actual, observed distance, which was maintained in the prior conversation.

Lastly, *unobtrusive techniques* are very naturalistic and observe persons in pre-arranged settings, such as a queue in an amusement park (Nesbitt & Steven, 1974). However, the experimental control is very low and the whole procedure complicated to repeat (Hayduk, 1978). For instance, it is very complicated to select subjects or obtain relevant characteristics of the sample (Hayduk, 1978). Furthermore, it is a rather inaccurate method and therefore unacceptable (Sobel and Lillith, 1975; Hayduk, 1978).

To date, the discipline of proxemics is still in need of methodological advancement (Harrigan et al., 2005; Uzzell, 2006). Many methods lack a satisfactory amount of reliability or comparability. In addition, a high sensitivity of personal space and interpersonal distances towards an enormous body of influencing factors, such as age (Meisels & Guardo, 1969), gender (Sobel & Lillith, 1975), social role (Gillespie & Leffler, 1983) or cultural background (e.g. Hall, 1966; 1973), has been well explored and needs to be considered in order to produce valid and comparable results. This topic is more detailed elucidated in the subsequent section.

To sum up, extensive research in human-human proxemics has been undertaken. Nonetheless, many uncertainties and open questions remain for the present work.

Precisely, it is unknown whether elaborated social space zones, the presumed shape of personal space, and explored interpersonal distances are also valid for a HRSI in a hallway. Moreover, no comparable human-human proxemics studies, specifically investigating accepted frontal or lateral passing distances, have been carried out in a hallway.

2.7.2 Influencing Factors on HHP

One vital step when conducting research in the field of proxemics is to know and consider potential influencing factors for properly designing experiments and thus, gaining valid and replicable results. This section introduces theoretical backgrounds and corresponding empirical findings in relation to the most relevant influencing factors on HHP.

As initially outlined in the previous section, personal and interpersonal distances are depending on a wide variety of other factors, such as gender, age, cultural and ethical background, body height, body size, interaction subject, situational factors, personal characteristics, interpersonal relationship or emotional state (Hall, 1966; Sommer, 1969; Hartnett, Bailey, & Hartley, 1974; Argyle, 1975; Burgoon & Jones, 1976; Gillespie & Leffler, 1983; Hayduk, 1983; Sommer, 2002a; Knapp, Hall & Horgan, 2013).

Hall (1966) proclaimed that the use and perception of personal space is affected by the constitution of the interaction space. This encloses fixed properties of the space itself (e.g. walls, doors), and semi-fixed features, such as movable elements in the space (e.g. furniture). His initial assumptions were expanded by distinguishing between a spatial and social density. Spatial and social density were defined by Hayduk (1983, p. 300) as *'the average space available to each person'* (spatial density), and *'number of participating individuals'* (social density). It has been widely shown that people prefer more space when they are under a low ceiling, in a narrow hallway or in a corner (Dabbs et al., 1973; Hayduk, 1983; Duncan & Murphy, 2013). For instance, conducted studies by Aiello, Thompson and Brodzinsky (1983) or Evans and Wener (2007) have shown an increased frequency of personal space violations in dense environments, such as a train/subway. Dabbs et al. (1973) observed that subjects' desired frontal personal space was greater when they stood with their back to a wall or corner. They assumed that these subjects perceived a higher level of threat and danger, which in turn might have made them more defensive.

By acquiring participants from two diverse cultures across experiments of the present thesis, it was essential to control the cultural background in order to obtain valid and comparable results. According to existing literature, it has been suggested that people can be divided into non-contact (North America, Northern Europe, Japan) and contact cultures (Arabs, Latin Americans, India, Southern Europeans; Hall, 1966; Watson, 1970; Hayduk, 1983; Nanda & Warms, 2010). Hall's (1966) spatial notation system is valid for non-contact cultures since he based his assumptions on observations with Northern Americans. Contact cultures have been reported to interact at much closer distances as well as touch one another more frequently (e.g. Hofstede, 2002; Ting-Toomey, 2012; Hall, 1966; Hayduk, 1983; Nanda & Warms, 2010). Hence, this effect was important to consider in the present work for attaining valid distance measurements.

With respect to gender, many inconsistent findings have been reported. Up to the point of Hayduk's proxemics review (1983), around 30 studies found sex effects and another 30 did not. For instance, Burgoon and Jones (1976) as well as Sobel & Lillith (1975) reported that females preferred greater frontal distances than males. In contrast, Lett, Clark & Altman (1969) found that females have smaller personal space zones than men. However, Hayduk (1983) pointed out that it is essential to consider possible confounding effects between age and body size, and the underlying differences in emotional states, objectives, fears and needs linked to gender differences. By considering a highly diverse body of knowledge, it was important for the present work to control and record this sample characteristic.

As already mentioned in the previous section, the human sense for spatial behavior is assumed to be learned at an early age (Aiello & Aiello, 1974; Sommer, 2002a). A wide range of studies has reported gradual increases in the size of personal space throughout the age range from 3 to 20 (Hayduk, 1983). It has been assumed that the corresponding increase in body size poses the main reason for this phenomenon (Hayduk, 1983). Therefore, the present work had to consider the age range of participants in order to permit robust interpretations for adults.

It has also been stated in literature that the body height plays an important role (Hartnett et al., 1974). In a field study, Caplan and Goldman (1981) observed that people invaded the personal space of a tall confederate significantly more often than of a small confederate. Researchers have assumed that tall people induce a higher level of threat to people, which in turn leads to greater interpersonal distances (Caplan & Goldman, 1981).

In line with assumptions regarding the body height, the body size of a person has also been reported to affect the size of personal space (Sommer, 2002a). In a series of studies it has been found that interpersonal distances increase towards fat people compared to normal or thin people (e.g. Lerner, 1973). This effect has been already found in an experiment with children using the *felt board technique* (Lerner, 1973). Assumed reasons mainly comprise the involvement of negative stereotypes towards very fat people (Lerner, 1973), or a higher degree of implied threat due to increased body sizes (Bailey, Caffrey & Hartnett, 1976).

Knowing and controlling the interpersonal relationship among interactants in an experiment, such as their level of familiarity, needs to be considered as well. Many findings have been obtained, showing that people interact in closer proximity the better they know each other (Hall, 1966; Burgoon & Jones, 1976; Hayduk, 1983). This was of partciularly relevance for the human likeness manipulation in the last study of the present project.

As already briefly mentioned in the previous section, Hayduk (1978) highlighted the importance of a constant walking speed for attaining reliable measurements during an experiment. In human-human proxemics literature, it has been presumed that the personal space dimensions surrounding a person are influenced by the walking speed (G´erin-Lajoie, Richards & McFadyen, 2005). Concretely, it has been stated that personal space increases by faster walking speeds (Kim & Branzell, 1995). However, no empirical evidence has yet been obtained.

Due to the reported existence of many other influencing factors, such as lightning conditions, greater distance preferences due to smoking or background noise (Hayduk, 1983), it was important to align situational features as much as possible throughout all experiments in the present work. Despite an intensive exploration and documentation of influencing factors on human-human proxemics, many studies have neither considered nor reported relevant sample or situational characteristics (e.g. Stratton et al., 1973; Hayduk, 1983). Thus, a comparison of diverse findings has been often complicated.

To sum up, this section unveiled a large body of research regarding personal space and interpersonal distance in relation to other factors. However, it remains open at this point to what extent this knowledge can be carried over to human-robot proxemics.

2.7.3 Human-Robot Proxemics

In this section, the related domain to human-human proxemics - human-robot proxemics - is introduced. The current state of knowledge, methodological approaches, challenges and uncertainties of this field are presented, which are of particular relevance for the overarching research problem of the present project.

Before the field of human-robot proxemics became popular, the social and personal use of space had already been investigated in another innovative field of research – virtual reality (VR). Many researchers, studying human-computer interaction or related fields, examined whether interpersonal distance adjustments in VR obey human spatial behavior in real life (e.g. Benford & Fahlén, 1993; Bailenson, Blascovich, Beall & Loomis, 2003; Friedman, Steed & Slater, 2007). For instance, Bailenson et al. (2003) confronted subjects with virtual standing humans in a virtual reality setting and instructed subjects to approach the virtual person from the front or back. In addition, the virtual person's gender and gaze behavior was varied and participants were also approached by the virtual character. Findings indicated that subjects maintained greater frontal distances than rear distances from the virtual person, and more mutual gaze caused greater interpersonal distances. In an earlier study, Bailenson, Blascovich, Beall and Loomis (2001) have also discovered findings which aligned to the previously explained *Argyle-Dean Intimicy Equilibrium Theory* (see section 2.7.1). It was observed that female subjects maintained greater interpersonal distances towards a virtual human who engaged them in eye contact. Furthermore, it is noteworthy that all subjects maintained greater distances towards a virtual human compared to a similarly shaped and sized non-human like object - a cylinder. The resulting distances were automatically tracked by the virtual system. Similar findings were obtained by Wilcox, Allison, Elfassy and Grelik (2006), who examined subjects' feelings of comfort towards stereoscopic images of animate (humans) and inanimate (objects) stimuli captured in three viewing distances (0.5m, 1.0m, 2.0m) and presented on a screen in a cave-like setting. Participants indicated greater levels of discomfort for images that showed humans than objects, and for all images which were captured from smaller distances.

Altogether, these empirical investigations have shown that negative feelings due to personal space invasions are also experienced in virtual realities. Thus, the existence and relevance of human-human proxemics has been also shown for human-computer interaction (Nassiri, Powell & Moore, 2010).

As already pointed out in section 2.7, the general relevance of an appropriate spatial behavior indisputably exists for interactions among humans and robots as well (Mutlu & Forlizzi, 2008; Takayama & Pantofaru, 2009). Human-robot proxemics poses a key feature of HRSI and *'...studies how humans and robots use and manipulate distances between each other with regard to social behavior and human perceptions'* (Asghari Oskoei et al., 2010, p. 9). Robots are physically embodied and actively produce social space as they move and act in a physical environment (Lindner & Eschenbach, 2011). But how are people's reactions and space preferences for approaching or passing robots?

2.7.3.1 Accepted Frontal Approach Distances in HRP

This section particularly focuses on specific explorations towards frontal approach distances in human-robot spatial interaction scenarios.

To date, only some studies have aimed to systematically explore acceptable frontal approach distances without involving any direct interaction, such as handing an object (Koay, Syrdal, Walters & Dautenhahn, 2007).

Walters et al. (2006) conducted an experiment, aiming to assess comfortable frontal approach distances between subjects and a mechanoid (the *PeopleBot* – see Figure 2-8), by applying the *stop distance technique*.

Figure 2-8 the PeopleBot (Adept MobileRobots, 2014)

Participants and the mechanoid were placed on opposite sides of a simulated living room (5.5m apart from each other) with scale marks at 0.5m intervals on the floor. Both experimental variations – a person approaching the standing robot to a comfortable distance and the robot approaching the standing participant to a comfortable distance – were video recorded in order to subsequently estimate the resulting distances. Walters et al. (2006) reported a measurement accuracy of 0.125m which is questionable, considering intervals at 0.5m. Attained findings revealed greater mean distances for robot to human approaches (0.88m) compared to human to robot approaches (0.71m). Furthermore, it was found that almost half (40%) of all participants approached the robot closer than 0.46m, and that 40% also accepted a robot approach right up to a pre-controlled minimal distance limit of 0.5m. Walters et al. (2006) assumed that participants simply did not perceive the mechanoid as a social entity similar to a human, instead they rather perceived the robot as an inanimate object. Apart from the rather inaccurate measurements, the robot to human safety constraint biased the assessed means. In addition, 50% of the subjects were recruited from a robotics or technology-related department and thus, had a prior familiarity with that robot. Potentially, a degree of robot familiarity may influence the results as it has been observed in HHP. Unfortunately, no cultural backgrounds of the subjects were recorded.

In a later experiment, Walters, Syrdal, Koay, Dautenhahn and Te Boekhorst (2008b) replicated these obversations in the same experimental setting. They enriched the previous experimental design by equipping the same mechanoid with diverse voice styles (male, female, synthesized, no voice). Again, subjects were asked to approach the robot to a comfortable distance and frontal mean distances were subsequently estimated by analyzing the recorded videos. In this experiment, no robot to human approach was conducted. In particular, the results of the control condition (no voice, mean distance 0.42m) showed many distances preferences within the intimate zone (< 0.46m) (Hall, 1966). In line with given reasons in the previous experiment, Walters et al. (2008b) assumed that the subjects perceived the robot as an inanimate object. In this experiment, a large majority of the subjects had prior experience with robots (83%), which possibly led to these small distances. This was corroborated by additional findings that revealed smaller minimum distances for subjects who had participated in an earlier experiment with the same robot on that day (subjects first encounter: 0.51m, subjects second encounter: 0.73m). Other voice variations provoked greater distances (male: 0,51m, female: 0,60m, synthesized: 0.83m). Walters et al. (2008b) suggested that participants did not expect a machine-like robot to talk, which possibly evoked a higher level of threat, which in turn is associated with a larger personal space, as introduced in section 2.7.1. Unfavorably, no ethnicities were recorded. In both studies, the distance was measured between the subjects' feet and the nearest opposite body part of the robot.

In another study using the PeopleBot, Koay et al. (2007) (from the same research group, cf. Syrdal, Koay, Walters & Dautenhahn, 2007) aimed to explore acceptable robot to human frontal approach distances in relation to subjects' level of familiarity with the robot, the robot's height (small: 1.2m, tall: 1.4m), appearance (machine-, human-like), autonomy (subjects in control, subjects not in control of the robot) and pursued interaction (verbal, physical, no direct interaction). Therefore, a small machine- and human-like, and a tall machine- and human-like version of the PeopleBot were designed, which is shown in

Figure 2-9 and 2-10. Furthermore, a '*comfort level device'* was provided to the subjects, which permitted to either stop the robot or triggered a distance recording of the laser scanner by pressing a button. This posed an essential novelty in HRP studies, permitting a higher reliability of acceptable frontal approach distances towards an autonomous robot.

In those trials, the robot autonomously approached the subjects up to a safety limit of 0.12m and subjects were requested to indicate their threshold of comfort by using the comfort level device during this maneuver. As common in many HRI studies, the robot was controlled by using a Wizard-of-Oz, which is explained in greater detail in section 2.7.3.5. It is important to note at this point that subjects were seated on a chair during the whole experiment. For exploring effects of the subjects' familiarity with the robot on distance preferences, the procedure was repeated three times over a period of five weeks (after one week, after two weeks, after five weeks). Unfortunately, only 12 participants took part in the complete procedure and no cultural background was recorded. However, in contrast to previous studies of this research team, recruited subjects showed a higher diversity of their academic backgrounds, but no prior level of a general robot familiarity was reported.

With respect to findings, the attained mean distances for diverse interaction scenarios showed smaller distances for a physical interaction (no interaction: 0.60m, verbal: 0.61m, physical: 0.48m) compared to the two other scenarios in the first encounter. Attained long-term data revealed significantly decreased mean scores for no and verbal interaction scenarios, but did not affect the physical interaction scenario in the fifth week (no interaction: 0.58m, verbal: 0.46m, physical: 0.49m). However, the decrease of the minimum distance for the '*no interaction scenario'* was very low. Upon the second repetition in the second week, no significant differences were attained, which was not further discussed. Furthermore, the robot's level of human likeness led to smaller minimum distances for the machine-like version (0.50m) than the human-like version of the robot (0.62m), but the robot's height did not lead to any significant effects, which was surprising, considering previously reported body height effects in HHP. Possibly, the established height difference was too low in order to affect subjects' distances preferences. Interestingly, the preferred distance towards the human-like robot decreased over time, which was not observed for the mechanoid. These phenomenons were unfortunately not further discussed. Moreover, the varied autonomy of the robot did not affect any assessed minimum distance.

In contrast to previous studies, attained mean distances, especially from the most comparable *'no interaction'* scenario, were within the personal zone. Unfavorably, no measurement details, such as the initial distance between subjects and participants, or the start and end point of the measured distance were reported. A further drawback, complicating the comparability of these studies, is posed by seating participants compared to standing ones in the previous studies. Moreover, this research team has not reported any speed levels of the robot.

Figure 2-9 small machine- and human-like versions of PeopleBot (Koay et al., 2007)

Figure 2-10 tall machine- and human-like versions of PeopleBot (Koay et al., 2007)

In contrast to findings of Walters et al. (2006, 2008b), an experimental home tour scenario with a *PeopleBot* unveiled heterogeneous observations (Hüttenrauch, Severinson

Eklundh, Green & Topp, 2006). In this study, subjects were asked to show the mechanoid around in a room. Subjects were tracked by using the on-board laser range finder and corresponding human-robot distances were assessed during the entire procedure. A crucial drawback of this study is posed by missing information regarding the start and end point of the measured distances between subjects and the robot. Findings indicated that only 10% of the sample operated with the robot within the intimate zone while a large majority of the subjects (75%) maintained distances within the personal zone (0.46m to 1.22m). Possible reasons for these contrary results opposed to the studies by Walters et al. (2006, 2008b) may involve diverse measurement techniques (floor markings vs. laser), a rather dynamic and direct interaction context in the study run by Hüttenrauch et al. (2006), or selected subjects who might had have no prior robotic experience. Unfavorably, Hüttenrauch et al. (2006) did not report any quantitative results, no estimated measurement accuracies, and no sample details like cultural background or prior robotic experience. Therefore, these findings are difficult to compare with the studies run by Walters and his colleagues (2006, 2008b).

Using the robot's onboard sensors to assess maintained frontal distances also served as a measurement technique in an experiment conducted with a *PR2* robot, which is shown in Figure 2-11 (Takayama & Pantofaru, 2009). The laser detected the subjects' legs which served as a reference point for assessing the final distance. Similar to Walter's et al. study (2006), human to robot as well as robot to human comfortable approach distances were tested. Importantly, subjects were instructed to approach the robot to the last point of comfort, or to step to the side when the robot surpassed their subjective threshold of comfort. In addition, the robot's head orientation was varied, resulting in facing subject's face or legs. Gained mean distances were almost all below 0.5m, except for participants who were pet owners. Unfortunately, no specific reasons for this effect were discussed. Furthermore, it was shown that subjects who had prior experience with robots (> 1 year) were comfortable with smaller distances compared to no prior robot experience. Lastly, the varied head orientation of the robot led to larger distances for women when the robot's head was facing their face. For men, the opposite was observed. Especially the last two findings were associated with similar findings in human-human proxemics. Thus, the study showed that a greater degree of familiarity with robots leads to decreases in people's personal space.

This finding simultaneously questions the validity of previously described studies by Walters et al. (2006, 2008b), who rather worked with experienced subjects regarding robots. In addition, the observed effects of the robot's head orientation also align to previous research in HHP, stating that mutual gaze causes larger interpersonal distances. However, observed effects for men were surprising. In contrast to previous work, employed starting positions for the robot and the subjects were only 2.4m away from each, which possibly led to a majority of accepted distances below 0.5m. Unfortunately, similar to Hüttenrauch et al. (2006), no cultural background of the participants was recorded, which limits the generalizibility and comparability of the data. Apart from a novel type of instruction, Takayama and Pantofaru (2009) were the first who reported the applied robot speed (v < 0.5m/s), which is seen as relevant and advantageous for replicating and advancing future knowledge based on comparable study details.

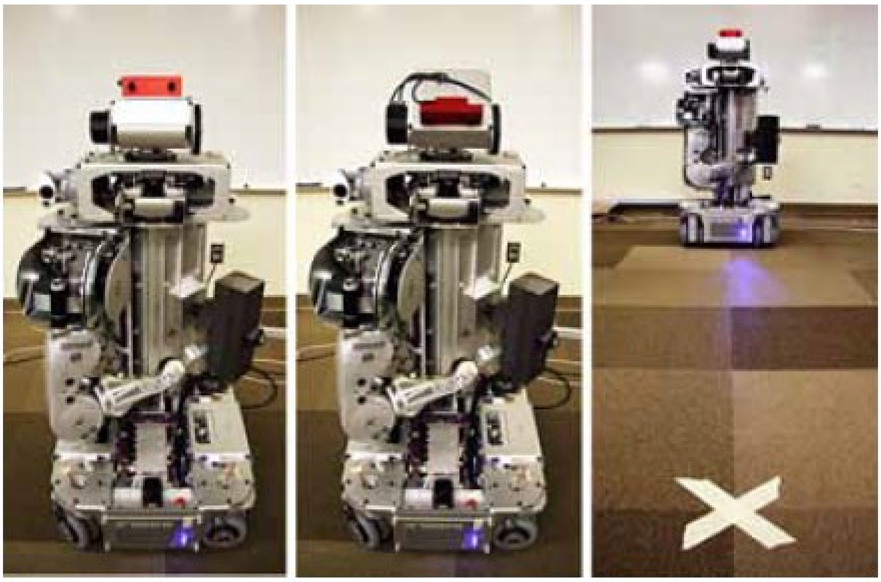

Figure 2-11 PR2 robot used by Takayama and Pantofaru (2009)

In a more recent study, Brandl et al. (2013) explored accepted frontal approach distances by using a care-o-bot (see Figure 2-12). 30 standing German participants were asked to stop the robot by pressing a button on a remote device as soon as the utilized mechanoid overshooted their subjective threshold of comfort. In an open room subjects and robot were positioned 5m away from each – similar to the study by Walters et al. (2006, 2008b) – and distances were assessed via a laser range finder with a reported accuracy of 0.02m. Unfortunately, Brandl et al. (2013) did not report any information regarding the start and end point of the measured distance between subjects and robot. The robot either approached the subjects with its front or rear side, and subjects were either standing, sitting or laying. In addition, the robot's speed was varied (0.25m/s, 0.5m/s, 0.75m/s). Obtained frontal mean distances varied between approximately 0.75m and 1.25m depending on the robot speed (0.25m/s = 0.75m, 0.5m/s = 1.0m, 0.75m/s = 1.25m). While the robot orientation (front, rear) had no significant influence, standing subjects maintained greater frontal mean distances compared to sitting subjects. In addition, laying subjects maintained the greatest frontal distances. Though Brandl et al. (2013) did not discuss any specific reasons for this effect, it can be assumed that body height effects, as observed in HHP, might also play a role in HRP. It is also imaginable that laying subjects might perceive a higher level of threat from an approaching robot. In regard to the effect of speed on personal space, this effect has been already presumed in HHP and has been additionally observed in other HRP studies as well, which is elucidated in greater detail in the proximate section.

It is noteworthy that subjects were introduced to the robot and its functionality. Moreover, subjects' prior robot experience was recorded. In contrast to previous studies, most of the subjects had not seen the robot prior to the experiment and had no high familiarity with robots in general. Accordingly, this study, in relation to the previous studies, additionally supports strong familiarity effects on HRP. Moreover, in contrast to studies run by Walters et al. (2006, 2008b) and Takayama and Pantofaru (2009), the robots possible approach distance was barely limited due to safety constraints (0.1m). However, accepted frontal mean distances were consistently greater than the intimate space zone. Thus, as already indicated by Hüttenrauch et al. (2006), this study showed that a majority of accepted distances lies within the personal zone. Together, this experiment generally posed a higher methodological accuracy and comparability to research objectives of this dissertation.

Figure 2-12 care-o-bot (left: front side, right: rear side) (Brandl et al., 2013)

In the most recent experiment, Kamide, Mae, Takubo, Ohara and Arai (2014) explored accepted frontal approach distances of a real humanoid compared to the same robot in virtual reality (VR). A graphical abstract of the study is presented in Figure 2-13.

Participants were requested to indicate their threshold of comfort by pressing a button, which in turn switched on an LED. By using subsequent video analysis, the resulting distance was then measured between the subjects' toe and the most forward point of the robot's face. The robot had three pre-programmed trajectories which differed in length and starting position as illustrated in Figure 2-14. For creating a similar experimental setting for the real robot as for the virtual robot, a hallway-like setting was designed. Unfortunately, no precise dimensions of this setting were reported. However, beyond the focus of this study, it has posed the first systematic evaluation of acceptable frontal approach distances in a hallway before the present work. The hallway-like setting is presented in Figure 2-15.

As in the study run by Takayama and Pantofaru (2009), the robot's and subjects' starting position were relatively close to each other (3.0m). Findings indicated an approximate frontal mean distance of 0.78m and no differences were obtained between the real and virtual robot. Accordingly, this study also supported previous findings that showed minimum frontal approach distances within the personal zone. Interestingly, all three approach types evoked the same minimum frontal mean distance, which is not in line with previously explained findings in HHP regarding an egg shape of personal space. However, the study did not precisely focus on that subject and the designed approaches did not laterally pass the subjects yet. Importantly, subjects had no prior experience with robots, which was in line with the study run by Brandl et al. (2013), but unfortunately, no robot speed was reported.

Thus, beyond diverse settings, robots, subjects and other measurement details, it is unknown whether the robot speeds were similar and thus, both studies could be potentially compared to each other. Furthermore, the study description lacks details regarding the cultural background of the subjects. Moreover, it is noticeable that mostly men participated in the study.

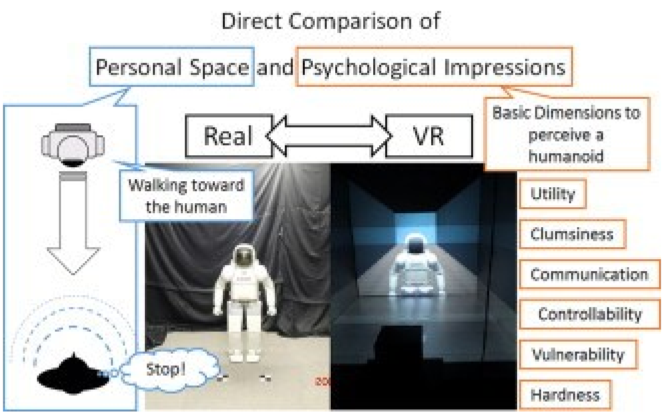

Figure 2-13 graphical abstract of the study (Kamide et al., 2014)

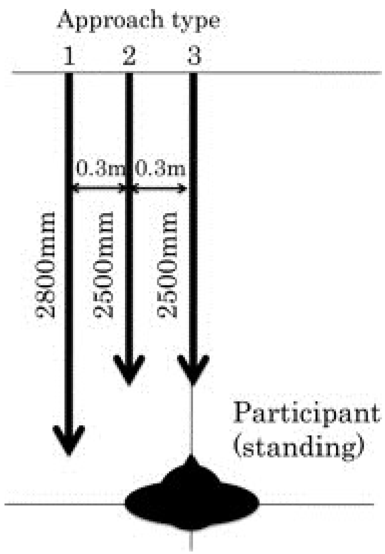

Figure 2-14 diverse trajectories and starting positions of the robot (Kamide et al. 2014)

Figure 2-15 hallway-like setting (Kamide et al., 2014)

Altogether, the review of existing studies, exploring frontal approach distances, poses a most commonly observed frontal distance for robot to human approaches within the personal zone, though a portion of inconclusive findings remains as well. This portion depicts disagreement in terms of some empirical indications for very close frontal distances (< 0.46m). Importantly, presented findings were based on diverse distance measurement methods, instructions, robots, settings, initial starting distances, robot velocities, different levels of prior robot familiarity or other sample details which include vital influencing factors on proxemics (e.g. culture). In addition, relevant methodological details or sample characteristics have been often not even captured or reported. In sum, this accumulation of drawbacks complicates a potential comparibility of studies and questions the level of reliability and validity of attained results. Furthermore, in most reviewed robot to human approach experiments (except Koay et al., 2007; Kamide et al., 2014), participants always controlled the distance behavior of the robots by saying stop, pressing a button, or moving away. Though these techniques provide a reasonable method to identify spatial thresholds of comfort, it remains questionable whether these methods apply for a proxemic evaluation of an autonomously moving robot. Initial indications of Koay et al. (2007) showed that an autonomously approaching robot did not affect subjects' distances preferences.

2.7.3.2 Accepted Lateral Passing Distances in HRP

In this section, previous research regarding the exploration of lateral passing distances is introduced.

Regardless of the vital meaning of lateral distances in everyday human-human scenarios, particularly in a narrow hallway environment, an examination of accepted lateral distances has been a very rare subject of investigation in HRP. Compared to accepted frontal approach distances, a significantly smaller body of studies is available to date.

By conducting two pilot studies, Pacchierotti and her colleagues (2005, 2006) uncovered initial insights into comfortable lateral passing behavior for a robot in a hallway. In the first study, they diversely modeled an autonomous passing behavior of a PeopleBot (see Figure 2-8) by altering its speed (0.5m/s, 0.6m/s), signal distance (4.0m, 5.0m), and lateral distance (0.3m, 0.4m). Signal distance is defined as *'…the distance of the robot from the person along the robot direction of motion (i.e. along the corridor direction) at which the robot starts the maneuver of passage and thus signals detection' (*Pacchierotti, Christensen & Jensfelt, 2005, p. 166). And lateral distance is defined as '… *the distance along the direction perpendicular to the corridor direction that the robot keeps from the person at the passing point, assuming that the person is walking straight along the corridor'* (Pacchierotti et al., 2005, p. 166). The modeled passing behavior is illustrated in Figure 2-16.

In total, only four subjects with prior robot experience were requested to walk along a 2.0m wide hallway as natural as possible while the robot performed the avoidance behavior. Upon experiencing each trial, participants rated their perceived level of comfort on a bipolar 5-point Likert scale. It is noteworthy that the examiners mentioned a discrepancy between desired and actually established motion features. In particular, the actual robot speed was lower during the maneuver due to the required turning moves. Furthermore, desired lateral distances resulted in actual smaller distances as well. Together, findings indicated that the highest robot speed and the greatest signal as well as lateral distance were preferred. It was assumed that subjects prefer a robot which moves faster to the side and signals its intentions as early as possible in order to increase its credibility and motion predictability.

A further interesting observation was made by classifying the subjects in two types: Those who considered the robot as a machine and those who considered the robot as a person. According to the authors' observation, some subjects made room for the robot (considered him as a person) and were more comfortable with its lateral distance, or some other subjects walked straight towards the robot to see the robot's reaction, which resulted in a lower level of comfort.

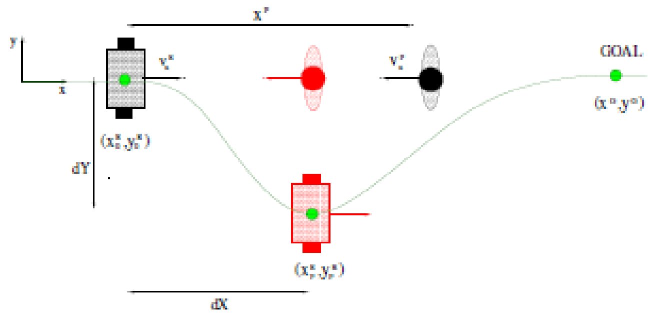

Figure 2-16 illustration of the modeled passing behavior (Pacchierotti et al., 2005)

In a follow-up study, Pacchierotti et al. (2006) specifically explored diverse lateral distances (0.2m, 0.3m, 0.4m) in a 2.5m wide hallway while they kept robot speed (0.6m/s) and signal distance (6.0m) consistent throughout all trials. Furthermore, the same robot and same instruction as in the previous experiment was applied. For increasing the reliability of the test, each trial was presented twice. Comfort ratings were assessed by using the same questionnaire as in the previous study upon each trial. In total, 10 participants with a balanced technical and non-technical background were recruited. As in the previous study, no information about the cultural background was captured. Findings indicated higher levels of comfort for the greatest lateral distance. In addition, initial indications, though not statistically relevant, were observed for an increased comfort level for repetitive trials, and for an increased comfort level for subjects with a technical background.

Taken together, both studies lacked of a sufficient number of participants (N=4, N=10) in order to obtain statistically relevant results. Nonetheless, the greatest lateral distance (0.4m) received the highest rating of comfort. As often seen in previously reported studies, no ethnical backgrounds were captured. In line with previously reviewed studies, initial indications were also found for lateral distances, which show that an increased level of robot familiarity tends to decrease preferred distances. Eventually, accepted lateral distances in a hallway need to be further investigated, which was realized in the present work.

2.7.3.3 Summary of Accepted Frontal and Lateral Distances in HRP

To conclude the previous two sections, it can be summarized that the concept of personal space is of high relevance among humans and robots. To date, research has empirically observed at least some of the richness of human-human proxemics in human-robot proxemics (Walters, Oskoei, Syrdal & Dautenhahn, 2011). It has been initially suggested that underlying psychological motives, potentially guiding human-human proxemics, also affect human-robot proxemics (e.g. threat, gaze behavior). However, this body of knowledge is still fragmentary and not all principles of human space conventions directly translate into human-robot proxemics (Takayama & Pantofaru, 2009; Sardar et al., 2012). For instance, whether suggested personal space zones in HHP also apply to general relations between humans and robots, or whether these zones also apply to indirect interaction scenarios remains questionable (Walters et al., 2006; Torta, Cuijpers, Juola & van der Pol, 2011). It has been also revealed that accepted frontal approach distances largely vary and several other inconclusive findings remain. In addition, almost all of the represented experiments worked with various robots, utilized different measurement methods, settings, subjects, or comprised further non-comparable variables. Surprisingly, though crucial influencing factors on human-human proxemics have been intensively studied, and reviewed HRP studies have also indicated similar effects (e.g. robot familiarity), a consideration of these factors has been rather poor. Accordingly, many studies can not be related to each other, are complicated to replicate and the results' level of reliability and validity is questionable. In sum, the body of knowledge is rather fragmentary to date.

This statement is in accordance with various other researchers in the field, stating that human-robot proxemics is still in its beginnings and demands much more exploration (Takayama & Pantofaru, 2009; Sauppé & Mutlu, 2014). In spite of an increased research attention in recent years (e.g. Walters, 2008; Kirby 2010; Duncan & Murphy, 2013), human-robot proxemics is still in need of a comprehensive model (Mumm & Mutlu, 2011), and many uncertainties remain (Greenberg, Marquardt, Ballendat, Diaz-Marino & Wang, 2011; Sauppé & Mutlu, 2014). Unfavorably, most studies are neither systematically conceptualized nor derived from any theory (Dautenhahn, Walters, Woods, Koay, Nehaniv, Sisbot, ... & Siméon, 2006) and thus, pose many drawbacks in terms of comparability and generalizability (Sauppé & Mutlu, 2014).

In regard to the specific context of this thesis, it can be further concluded that existing literature provides initial indications for frontal approach distances and lateral distances within human-robot proxemics. Anyhow, findings have also demonstrated distinct perceptions of adequate frontal distances in human-robot proxemics (Torta et al., 2011). In general, it has been postulated that the personal zone (0.46m to 1.22m) seems to be the most adequate spatial zone in HRI (e.g. Hüttenrauch et al., 2006) and that a lateral passing distance of 0.4m is more comfortable than 0.3m or 0.2m (Pacchierotti et al., 2005, 2006). Furthermore, it was shown that a hallway-like setting has rarely been investigated yet. In addition, only few studies have been undertaken which addressed frontal distances during encounters not aiming to initiate a direct interaction, such as handing an object or starting a conversation. In addition, the existing body of research has not yet systematically explored accepted lateral passing distances in a hallway. Moreover, most research has not been focused on an exploration of frontal and lateral distance preferences toward an autonomous mechanoid in a hallway.

2.7.3.4 Influencing Factors on HRP

In the present section, an overview of the current state of knowledge regarding influencing factors on people's distance preferences in HRI is introduced. Additionally, relevant factors for the present work are elucidated in greater detail.

Walters and his colleagues have conducted a large series of HRP experiments, incorporating manifold influencing factors. Corresponding findings were excellently summarized in an empirical framework for HMP, which is illustrated in Figure 2-17. The framework indicates influencing factors on frontal approach distances which have been empirically found to be significant. An overall mean of 0.57m was assessed and all distances are presented as relative differences from this mean value (Walters, Dautenhahn, Te Boekhorst, Koay, Syrdal & Nehaniv, 2009). Due to the focus of the present work on acceptable frontal approach and lateral passing distances in a hallway, not all of these experiments were reviewed in greater detail.

Factor	Situation(s)	Context(s)	Base Distance = 57cm Estimated Adjustment for Factor (± 0.5cm)
Attribute or Factor of Robot			
Mechanoid Robot	RH Approach HR Approach	All	-3 -7
Humanoid Robot	RH Approach HR Approach	All	+3 -1
Verbal Communication	RH Approach	Verbal Interaction	+3
Giving object	RH Approach	Physical Interaction	-7
Taking object	RH Approach	Physical Interaction	-7?
Passing	RH Approach	No Interaction	+4
Direction from:	RH Approach	Front Right/Left	+2 -2
Attribute or Factor of Human			
Preferred Robot Humanoid	RH Approach	All Private	-3
Preferred Robot Mechanoid	RH Approach	All	+3
Preferred Height Tall	RH Approach	All	-1
Preferred Height Short	RH Approach	All	+2
Uncertainty or perceived inconsistency	HR Approach	Initial Encounter	+13
Verbal Communication	HR Approach	Verbal Interaction	+3
Giving object	HR Approach	Physical Interaction	-7?
Taking object	HR Approach	Physical Interaction	-7?
Passing	HR Approach	No Interaction	+4

Figure 2-17 - empirical framework by Walters et al. (2009)

Beyond this framework, as already unveiled in the previous section, several other factors have been also shown to affect distance preferences. The most relevant for the present work are subsequently summarized.

Though a mechanoid's movement behavior is limited in its physical capabilities opposed to a human, robot speed is seen as an equally relevant property of robotic motion behavior (Butler & Agah, 2001; Paccherotti et al., 2006). As presumed in HHP (Hayduk, 1978; Kim & Branzell, 1995), robot speed seems to influence subjects' distance preferences in HRP (Brandl et al., 2013). As previously reviewed, Brandl et al. (2013) obtained findings that demonstrated increased frontal minimum distances due to increased robot speeds, which is in accordance with findings in HHI. In particular, it was observed that an increased robot speed of 0.25m/s led to greater frontal mean distances of 0.2m. The similar effect was found in an early study by Mizoguchi et al. (1997). One could also take attained findings by Paccierotti et al. (2005) as a positive indication for this effect. Though they did not systematically explore this relation, findings indicated greater comfort ratings for greater robot speeds and distances. Unfavorably, most represented studies have not reported any speed levels of the employed robots which complicated potential inter-study comparisons. In fact, robot speed and its influence on proxemics has not been addressed any further in HRP.

In accordance with the previously described study by Koay et al. (2007), one further experiment has revealed that a human-like appearance of a robot tends to increase subjects' personal space. In an early study, Butler and Agah (2001) exposed people either with a very small mechanoid (Nomadic Scout) or a big stylized humanoid (robotic base with a human-like mockup body). Unfortunately, no good image material is available of these robots. In addition, no distances were assessed, but subjects' subjective impressions of comfort, which indicated that participants preferred greater distances towards the humanoid. The authors assumed potential confounding effects with the robot's size, stating that the humanoid takes considerable more space in the room and thus, might appeared more menacing. Apart from these studies, no further experiments have specifically addressed potential effects of a robot's level of human likeness on proxemics. It is important to mention at this point that a robot's level of human likeness is referring to its outward appearance and not to other robot features, which potentiall could reinvoke a higher degree of human-likeness (e.g. human voice styles). In retrospect, Koay et al.

(2007) found that people preferred greater frontal distances towards a humanized PoepleBot compared to the orginial, machine-like version of the robot. Unfavorably, this phenomenon was not any further discussed. In addition, the presented incomparable characteristics of reviewed HRP studies complicate an inter-study relation of experiments that employed mechanoids (e.g. Walters et al., 2006; Brandl et al., 2013) and those that employed humanoids (Kamide et al., 2014).

As already assumed and empirically proved in HHP (Hall, 1966; Aiello et al., 1983; Hayduk, 1983; Evans & Werner, 2007), spatial density affects personal and interpersonal spaces. Therefore, one might also assume that a higher spatial density of an environment, such as a hallway, may increase distance preferences towards a robot. Unfortunately, no studies have systematically investigated this subject for HRP yet (Peters, Spexard, Hanheide & Weiss, 2011). Most research, as previously introduced, has been conducted in large rooms or no specific comparisons between larger and narrower environments have been experimentally addressed. Initial evidence has been provided by a study of Walters, Koay, Woods, Syrdal & Dautenhahn, 2007). In line with results in HHI, the conducted study showed that accepted frontal approach distances during a *'fetch and carry'* scenario were significantly increased when participants were standing close to a wall with their back. By exploring comfortable frontal approach distances with older people in two diverse settings (open living room, smaller and narrower kitchen area), Walters et al. (2011) did not find any significant distance differences. However, the study only contained seven subjects and qualitative data of the study revealed that participants seemed to rather anticipate physical interactions with the robot in the kitchen compared to the living room. All in all, the effects of spatial density remain largely untested to date. However, reviewed studies suggest that more dense environments, such as a hallway compared to a large room, may lead to diverse distance preferences in HRP.

As widely shown in HHP (Hall, 1966; Burgoon & Jones, 1976; Hayduk, 1983), several HRP studies have already revealed significant evidence for the effects of familiarity with a robot or with robots in general. As reviewed in the previous section, studies of Koay et al. (2007) or Takayama and Pantofaru (2009) have obtained evidence for decreased distance preferences due to increased level familiarity with robots. In addition, Walters et al. (2011) found that accepted frontal distances particularly decrease for the second exposure to a robot. Though this finding was not in line with gained results from Koay et al. (2007), demonstrating that significant decreases firstly occurred after the third exposure, it generally supported the effects of familiarity as well.

Though cultural differences in HHP have been found to influence proxemics (Hall, 1966; Hayduk, 1983; Nanda & Warms, 2010), an exploration of cultural differences on HRP is rare. Initial evidence has been obtained recently by Eresha, Haring, Endrass, Andre and Obaid (2013), who systematically investigated distance preferences of German and Arab subjects towards a humanoid robot (NAO). The experimental procedure comprised two scenarios. First, subjects were requested to imagine a conversation scenario of two robots and were asked to position the robots according to their own distance preferences. Second, subjects had to do the same, but were additionally requested to also place themselves to be part of the conversation. Subsequently, the resulting distances were measured. Findings showed that Arabs arranged themselves and the robots at closer interpersonal distances (0.65m) than Germans (0.85m). These results also suggested that subjects seemed to prefer inter-robot distances which suits their own interpersonal distances according to their cultural background. Taken findings from HHP and this first study together, it seems careless to neither capture nor record ethnicities, as seen in most previously reported HRP studies. Limited degrees of validity are inevitable and inter-study comparisons are complicated.

Height poses a further relevant robotic feature for the present thesis, considering the two employed mechanoids, which largely differ in their height. Effects of body height on human-human proxemics have already been reported (Hartnett et al., 1974; Caplan & Goldman, 1981). However, as already noted in the study description of Koay et al. (2007), the designed height difference of the PeopleBot (1.2m, 1.4m) did not affect subjects' distance preferences. Similar findings were attained by Duncan & Murphy (2013), who examined comfortable approach distances towards a small unmanned aerial vehicle (SUAV). The flying robot was approaching the subjects either above or below head height and the ensuing comfort was evaluated by applying the *stop distance technique* as well as subsequent interviews. Findings revealed no significant differences regarding the subjects' behavior and comfort ratings. Though this study provides a further non-significant indication, actual robot heights were not varied and thus, this subject remains largely untested. To date, one more study addressed this subject.

In a field study, Oosterhout and Visser (2008) employed two diversely looking robots (Mobi Sr. and Mobi Jr.), which differed in their height by 0.63m. However, the robots did not exclusively differ in their height, which complicates a complete attribution to this effect (see Figure 2-19). The observation aimed to evaluate the influence of the two robot types and people's age on human to robot approach distances. Findings across all age groups suggested greater maintained distances towards the taller robot (tall robot: 1.58m, small robot: 1.38m). However, this phenomenon was not any further discussed. As already noted as very common problem in HRI/HRP, all of these studies utilized incomparable robots, methods, samples and settings, which could have led to these controversial results. Furthermore, conceivable relations between robot height and size have not been addressed yet.

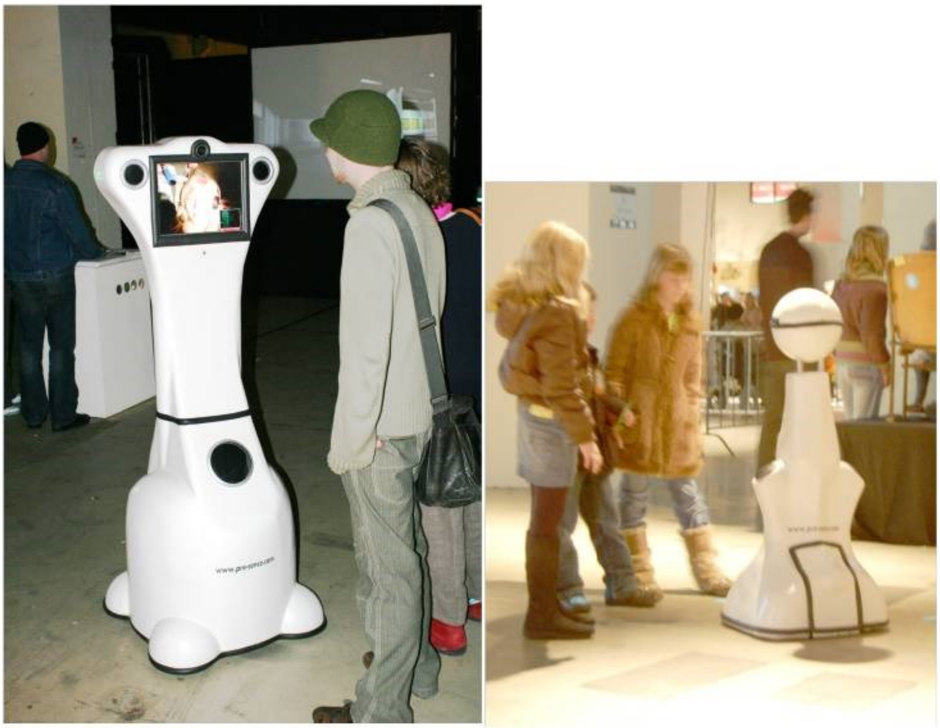

Figure 2-18 left: Mobi Sr. (tall), right: Mobi Jr. (small) (Oosterhout and Visser, 2008)

A further interesting observation in HRP is posed by an empirically revealed effect of robotic gaze behavior on subjects' distance preferences. Similar to obtained effects in HHP, mutual gaze behavior of a robot and a human has been shown to increase the comfortable distance between a robot and a human (Takayama & Pantofaru, 2009; Mumm & Mutlu, 2011). Initial results have been obtained by Takayama & Pantofaru, which is described in the previous section. They have found that a robot's head, facing subjects' faces, evoked greater desired frontal distances. In a later study, Mumm & Mutlu (2011) specifically addressed this subject by manipulating a robot's gaze behavior (mutual, averted gaze). The employed robot was a humanoid and had a human-like head with human-like eyes. Subjects were asked to position themselves towards the robot and the resulting self-distancing was measured. Obtained findings showed that a mutual gaze behavior increased subjects' distance to the robot when the participants generally disliked the robot. However, this compensatory behavior did not occur when the robot was generally liked, which has not been any further discussed.

In sum, a wide range of influencing factors on HRP has been uncovered. It has been shown that relevant influencing factors, such as spatial density, familiarity and cultural background, require consideration when designing HRP experiments. Furthermore, this review highlights that only a few explorations of a robot's speed or human likeness and its relation to people's personal space exists. In addition, the influence of these factors has not at all been investigated for acceptable lateral passing distances. Though initial indications can be derived from previous experiments, further explorations are necessary to enrich the current state of knowledge. In general, all of the addressed aspects have not been explored in a hallway setting yet. All in all, the reviewed body of knowledge remains rather fragmentary and aligns with previously stated problems, posing a complicated comparibility.

2.7.3.5 Methodological Approaches in HRP

In this section, methodological approaches in HRP are reviewed and summarized. As already highlighted in the previous sections, several aspects need to be considered when designing HRP experiments in order to attain reliable, valid, replicable and thus, comparable findings.

Altogether, many different distance measurement approaches have been pursued in the reviewed studies. The approaches can be summarized as follows:

1. *Stop distance techniques*
    a. measured via measurement grids or scales on the floor
    b. measured via subsequent video analysis
    c. measured via the robots' on-board sensors

2. *unobtrusive measurement techniques*
    a. measured via digital photographs

3. *robot placing techniques*
    a. measured via subsequent distance assessment

Given the reported measurement accuracies of diverse stop distance techniques, best results have been reported for the laser scanner (0.02m, Brandl et al. 2013). Reported accuracies for measurement scales and subsequent video analysis of the distance were considerably lower (0.125m, Walters et al., 2006). In addition, some studies that applied those techniques have not even reported any measurement accuracy (Kamide et al., 2014). Thus, using a robot's laser scanner seems to be clearly advantageous. In addition, sensor-based data collection has been postulated to avoid time-consuming manual observations (Walters, 2008). Most advantageously, sensor-based findings rather rely on a possible technological realization, which is of substantial relevance for implementing gained knowledge into a future real-world application (Walters, 2008). Furthermore, relevant distance effects have been posit to refer to changes in a range of 0.02m to 0.1m (Walters et al., 2011), which highlights the requirement of utilizing more accurate measurement techniques. Walters (2008) also noted a potential influence of metric scale marks on participants' subjective distance perceptions. Hence, human-robot proxemics measurement tools should rather not involve floor distance indicators. In sum, stop distance techniques pose the most appropriate technique to explore accepted distances between humans and robots.

An unobtrusive measurement has only been performed in one study to date (Oosterhout & Visser, 2008). By taking digital photographs of the interaction scenarios and knowing the precise dimensions of the robots, ratios between pixels and centimeter were established and thus, distances could be assessed. Unfortunately, no precise measurement accuracy has been reported and this method also seems to be less feasible and less time-efficient compared to stop distance techniques. However, this method poses an applicable approach for uninformed field tests. In favor of unobtrusive methods, HHP research showed a decrease in personal space by approximately 8% when participants knew about the purpose of measuring it (Hayduk, 1978). Thus, unobtrusive measurements in HRP may avoid this effect, but this remains untested to date.

Instructing subjects to place themselves to a robot or robots to each other has also been applied only once to date (Eresha et al., 2013). Though distance assessments are accurately measurable, this method is only valid for exploring a static setting, which is of less relevance for the highly dynamic characteristic of HRI. In addition, similar to felt board techniques in HHP, this method relies on the cognitive abilities of the subjects, which may bias the results.

Beyond the overall type of measurement approach, many further relevant details need to be considered.

Within human-robot distance experiments a wide variety of defined distance dimensions exists, such as taking the distance from the closest body part of the robot to the subjects' feet (Walters et al., 2006), taking the distance between the robot's laser range finder and the subjects' legs (Takayama & Pantofaru, 2009), or taking the distance from the robot's shell to the point directly under the center of the subjects' torsos (Oosterhout & Visser, 2008). In other studies, this crucial criterion has not even been reported in detail (e.g. Brandl et al., 2013). Accordingly, by establishing a standard measurement dimension for human-robot proxemics, experimental studies would increase the degree of direct comparability (Walters, 2008). Therefore, Walters (2008, p. 175) proposed a working standard which he defined as: '*The distance between a human and a robot to be that measured between the nearest opposing static body parts of an interacting human and robot, but not including any arms or manipulators reaching out'*. It is important to note that closest body parts strongly depend on the size and shape of the robot as well as on the biometrics of a human (Hayduk, 1978). This was taken into account across all distance measurements in the present thesis.

Apart from the measured distance between humans and robots, one should also consider the initial distance between the interactants' starting positions. As already noted in the study descriptions, these distances largely vary within HRP experiments. Whether this might affect people's distance preferences, however, remains unknown. To avoid potential bias, the present work kept the initial distance consistent throughout all conducted studies.

A further relevant factor to consider is constituted by the chosen method of participants' comfort or discomfort indication. Most pursued approaches (subjects in control of the robot) are not valid for an exploration of an autonomous robot since people will not control a robot's behavior in the field. Hence, these findings only provide initial indications and should be re-tested with autonomously approaching robots that participants do not control. Other approaches, comprising no subjects' control of a robot's distance (e.g. comfort level device, Koay et al., 2007), potentially minimize this problem, but simultaneously lead to other drawbacks, such as minimum distances due to safety constraints or a missing real stopping experience for the subjects. In the present work, a novel methodology is presented, which aims to improve these issues.

It is also essential to distinguish between instructions, asking participants to indicate comfortable (e.g. Walters et al., 2006) or uncomfortable distances (e.g. Brandl et al., 2013). Since a robot should primarily avoid a violation of humans' personal space, arising feelings of discomfort and corresponding distances are of higher relevance for practical implementations. This approach was also pursued in the in the present work.

Another frequently varied experimental factor across human-robot distance studies is the selection of the actively approaching interactant and the passively approached one. A first study revealed indications for greater frontal distances for robot to human approaches than human to robot approaches (Walters et al., 2006). In a later study by Takayama and Pantofaru (2009), these effects were not significantly obtained. Another study supported Walters' et al. (2006) findings by showing greater minimum distances when being approached by a robot than approaching a robot (Walters et al., 2011). In regard to practical implications, a robot to human approach is of higher relevance and was applied across all distance experiments in the present research project.

As in many other scientific disciplines, human-robot proxemics is confronted with a discrepancy of internal validity against external validity. Exploring human-robot interactions in the field has been posit to be the best method for observing insights into people's expectations and preferences towards social robots (Sabanovic, Michalowski & Simmons, 2006). Nonetheless, controlled laboratory studies are necessary in order to reduce potential effects of confounding variables (Howitt & Cramer, 2007).

In addition, current robotic systems still pose a wide range of technological challenges regarding a highly controlled and consistent reproduction of motion behavior. For maintaining diverse distances in a systematical and controlled manner, one commonly applied workaround has been established: the Wizard-of-Oz method (Dahlbäck, Jönsson & Ahrenberg, 1993). It has been employed in numerous HRI studies and particularly in human-robot proxemics studies (e.g. Green, Hüttenrauch & Severinson Eklundh, 2004; Walters et al., 2006; Hüttenrauch et al., 2006). In general, this research methodology simulates specific functions or behaviors of a future autonomous robotic system that would be either extremely time- and/or cost-consuming, or even technically impossible to realize (Walters, 2008). Instead, the Wizard-of-Oz is an examiner's disguised confederate who secretly controls the experimental robot platform (Green et al., 2004; Walters, 2008). This method is also applied in the last study of the present thesis.

In conclusion, this section highlights the importance of taking into account a wide body of methodological details when experimenting in the field of human-robot proxemics. Given the potential differences in designing a human-robot distance experiment, it is crucial to utilize measurement techniques with a high degree of reliability. Additionally, already evaluated measurement standards should be applied carefully. Moreover, it is essential to control potential influencing factors in order to relate empirical results to each other and generalize them to other types of robots, people or contexts. To date, the discipline of human-robot proxemics still needs a higher degree of common consensus towards specific methodological standards, which would significantly contribute to an increased comparability across empirical studies.

2.7.3.6 Influence of Robotic Distance Behavior on Motion Acceptance

In the last section of this chapter, available theoretical backgrounds and findings of robotic distance behavior on the overall motion acceptance of a robot are presented. Moreover, this section poses an important theoretical base for the elaborated and applied questionnaire in the present work, assessing the overall motion acceptance of a robot.

As already mentioned, proxemics pose an important feature in daily HHI (e.g. Hall, 1966; Hayduk, 1983). In line with its relevance for HHI, appropriately calibrated frontal approach and lateral passing distances have been also found to be relevant for a social robot, operating in human environments (e.g. Walters, 2008; Pacchierotti et al., 2006). However, it is largely untested to what extent an appropriately designed proxemic behavior of a robot affects the overall motion acceptance. Thus, as listed in the beginning of this dissertation, the exploration of this subject is a pursued research goal of this research project. Unfortunately, no standardized measurement tool has yet been developed to assess the motion acceptance of a robot.

Not surprisingly, the social acceptance of social service robots is a crucial dependent variable. It has been postulated to reflect a central metric, assessing the outcome of a specific relation between a social robot's external design and behavior (Mizoguchi et al., 1997; Lohse & Hanheide, 2008). Furthermore, it has been widely used in several human-robot interaction studies and has been particularly applied to avoid aversion against social robotic systems (Lohse & Hanheide, 2008). Unfavorably, social acceptance has been often discussed and used as a general measurement dimensions, assessing whether humans generally accept the robot in their environment or not (Breazeal, 2004b). Therefore, existing social acceptance tools do not permit an acceptance assessment of single robot features, such as the robot's motion behavior (Breazeal, 2004). Unfortunately, this poses a drawback for an exploration of single features' relevance for the overall social acceptance, which in turn would permit to design robot behavior and appearance, according to the relevance of single robot features for the overall social acceptance.

As already mentioned before, Oestreicher (2007) has run an essential pilot study, aiming to assess the importance of single robot features for the overall social acceptance. As previously outlined, subjects were instructed to rate different robot features, such as human likeness, safety, size, general social behavior, or distance behavior, according to their importance for a positive appreciation in a common environment. Obtained findings showed that a robot's human likeness seemed to be less important than social behavior, such as appropriate distance behavior (Oestreicher, 2007). Apart from an appropriate distance behavior, the robot's speed and agility have been also mentioned to be of high relevance for the overall social acceptance. Furthermore, the perceived level of trust and safety towards a robot seemed to be important. Interestingly, when participants were asked for robot features that were most important in creating negative feelings, high ratings were attained for unexpected stopping maneuvers of the robot and hardly understandable actions. Thus, these findings indicate that a robot's motion behavior and corresponding motion acceptance seems to play a crucial relevance for the overall social acceptance. Accordingly, the present work aims to assess the motion acceptance of the employed robots.

Towards conceptualizing a reliable and valid questionnaire for the present work, already existing acceptance models and methods were considered and are subsequently introduced. In general, acceptance is a complex construct and has been broadly investigated during the past decades (Weiss, Bernhaupt, Tscheligi, Wollherr, Kuhnlenz & Buss, 2008). It was defined by Dillon (2001) as *'the demonstrable willingness within a user group to employ technology for the tasks it is designed to support'*. Within diverse theoretical models, very frequently cited key variables, which determine individual acceptance towards technology, are *perceived usefulness* and *perceived ease of use* (Dillon, 2001; cf. Davis, Bagozzi & Warshaw, 1989). In more recent robotic literature, acceptance has been primarily linked to crucial dependent variables, such as *'using intention'* or *'actual usage'* (Weiss et al., 2008).

Based on this understanding of acceptance and on a detailed literature analysis, Venkatesh, Morris, Davis and Davis (2003) elaborated the most prominent acceptance model in robotics: the Unified Theory of Acceptance and the Use of Technology (UTAUT). It encompasses a broader range of constructs influencing acceptance, such as performance expectancy, effort expectancy, attitude towards using technology, self-efficacy, anxiety and behavioral intention to use (Venkatesh et al., 2003). It is important to note at this point that many of these constructs are complicated to apply to the research context of the present work. Given the exploration of accepted frontal approach or lateral passing distances, no efforts of the subjects or use intentions are of any relevance.

Furthermore, it is of particular importance to note that the underlying understanding of this acceptance model is based on a direct interaction between a human and a robot, such as handing an object, putting something on a robot's tray or verbally interacting with a robot. Therefore, this acceptance assessment technique needed to be adapted to the specific research context of the present work. Nonetheless, the UTAUT model provided a theoretical starting point for the present work.

2.8 Chapter Summary

To sum up and conclude the theoretical foundation of this dissertation, several points have to be considered:

First, the gradually emerging novel era of social service robots, operating and collaborating with humans in their everyday environment, highlighted the substantial requirement for this sort of robot to exhibit socially appropriate behavior. Exploring a socially adequate interaction of humans and social robots is the central subject of the fairly young discipline HRI. Given a high complexity and many incomparable findings to date, the overall body of knowledge still lacks comprehensive theories and models. In addition, popular, but largely untested debates regarding the most suitable robot appearance or the Uncanny Valley, have primarily occupied the scientific community and have led to a neglected research focus on socially appropriate non-verbal behavior of a robot, such as motion behavior.

Second, several studies have revealed evidence for resulting positive effects on people's feelings and attitudes towards robots due to adequate robotic social behaviors. In particular, the relevance of robotic motion behavior for a robot's social acceptance has been demonstrated. However, robots are not people and it is unlikely that humans expect the same social reactions from robots as from humans in comparable contexts. Thus, to what extent a socially deployed mechanoid should adhere its motion behavior to underlying human principles has posed a key question to date. This issue is well-reflected in the central field of this dissertation – human-robot spatial interaction.

Third, similar to human-human spatial interaction, the humans' personal and social use of space – proxemics - was equally highlighted for acceptable spatial interactions among humans and robots. Theoretical backgrounds of human-human proxemics, corresponding psychological motives and experimental approaches were introduced. In addition, the complexity of this field, incorporating manifold influencing factors, was represented.

Fourth, the existing body of knowledge (HRP), which is directly relatable to the overarching research questions of the present dissertation, was presented and reviewed. Findings primarily revealed acceptable frontal approach distances in the personal zone (0.46m to 1.22m) and initial indications for comfortable lateral passing distances (0.4m) in a hallway were reported from a pilot study. In addition, the existing small body of findings, regarding the influence of a robot's speed and human likeness on people's distance preferences, was expounded. Importantly, the potential influence of these factors on acceptable lateral distances has not been explored yet. Altogether, several research gaps and drawbacks in this body of knowledge, such as lacking hallway studies, lacking explorations of acceptable lateral passing distances, lacking levels of measurement accuracies and standards, highly lacking generalizability of results and many prevailing controversies, were pointed out. Accordingly, the presented literature review corroborated the necessity for the conducted research in the present work.

Fifth, it was shown that previous work, regarding a robot's acceptance, can be carried over to a limited extent to the present research context. However, no measurement tool assessing a robot's overall motion acceptance has been elaborated yet.

Altogether, no systematically conceptualized evaluation of a HRSI in a hallway has yet been conducted. Accordingly, an appropriate adjustment of frontal and lateral distances between a standing person and an autonomously approaching or passing robot in a hallway is unexplored. Additionally, the influence of robot speed and human likeness on people's distance preferences demands further investigation. Lastly, the relevance of a robot's proxemic behavior for the overall motion acceptance has not been investigated yet.

3 Study I: Exploration of Accepted Distances Toward a Non-autonomously Approaching and Passing Mechanoid (Transport Assistant) in a Hallway

As previously expounded in the literature review, proxemic research generally lacks methodological accuracy and comparability. In addition, reviewed study results can neither be transferred from human-human nor human-robot proxemics research to the specific research context of the present project. Therefore, this initial study primarily aims to systematically attain an empirical starting base to develop hypotheses for successive studies of this dissertation. At this point, accepted frontal as well as lateral distances are explored by putting the mechanoid in control of the participants. By requesting the subjects to stop the robot or place themselves at a distance of arousing discomfort, frontal and lateral mean thresholds of comfort are assessed.

Concretely, the following research questions are addressed:

1. Which frontal mean distance does a standing person accept from a non-autonomously approaching mechanoid in a hallway?

2. Which lateral mean distance does a standing person accept from a non-autonomously passing mechanoid in a hallway?

3. Are these distance preferences influenced by the mechanoid's speed?

Given presented indications of accepted frontal robot to human approach distances, which were primarily found within the personal zone of the presented personal space notation system (Hall, 1966), greater accepted frontal mean distances than 0.46m are expected. According to the assumed asymmetric personal space shape around a human (e.g. Ashton & Shaw, 1980) and initial insights from Pacchierotti et al. (2005, 2006), accepted lateral distances are supposed to be smaller than accepted frontal distances. Lastly, reported effects of the robot's speed on personal space (e.g Brandl et al., 2013) are taken into account. Accordingly, a faster robot speed is predicted to result in greater accepted frontal as well as lateral mean distances.

In sum, the following three hypotheses were formulated:

Hypothesis I: *The accepted frontal mean distance will be greater than 0.46m.*

Hypothesis II: *The accepted lateral mean distance will be smaller than the accepted frontal mean distance.*

Hypothesis III: *A faster speed of the mechanoid will increase subjects' distance preferences.*

This study has already been published in the conference proceedings of the 23rd IEEE International Symposium Robot and Human Interactive Communication (Lauckner, Kobiela & Manzey, 2014).

3.1 Method

3.1.1 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 US 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%) were not involved with any kind of autonomous systems. Lastly, 21 (60.0%) subjects had never seen the used mechanoid before, nine (25.7%) subjects 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.

3.1.2 Material

The present study was conducted in the robotics 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 6m long and 2.90m wide. These dimensions were chosen to ensure a sufficient amount of space regarding the experimental variations. In addition, the chosen hallway width approximately resembled a common hallway size in a hospital or a larger office space. Blue markings on the ground indicated the starting position of the robot and the participants. Initial positions of the subjects differed from each other depending on the pursued exploration of accepted frontal or lateral distances. Within experimental trials exploring frontal distances the robot started 4.5m in front of the subjects. All trials comprising the exploration of lateral distances marked a subjects' starting position 3.2m in front of the mechanoid and 1.2m to the left of the mechanoid (from the mechanoid's point of view). The laboratory hallway-like setting is shown in Figure 3-1 and Figure 3-2.

As already indicated in the beginning of this dissertation, the prototypic *'transport assistant'* was employed across the first two studies of this dissertation. For a closer description of the robot's technical details and appearance see section 1.4. It is important to note that the mechanoid's acceleration behavior was constantly set to $2 m/s^2$, respectively $-2 m/s^2$ resulting in a relatively prompt stopping and accelerating.

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 mechanoid's forward and stop motion.

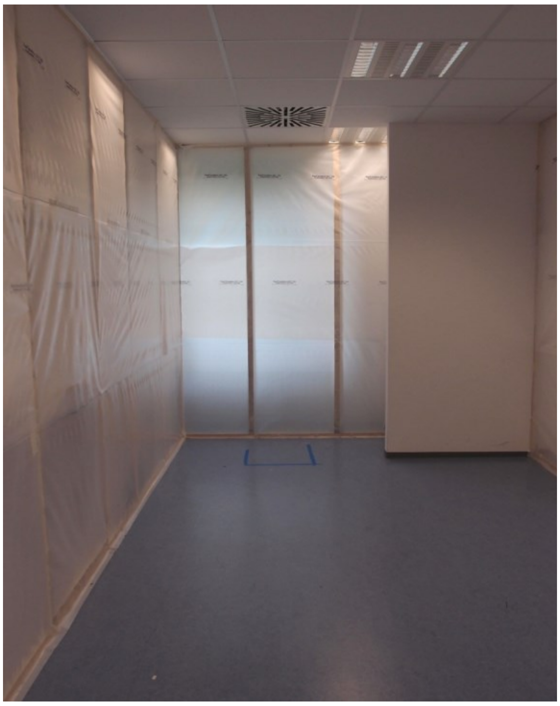

Figure 3-1 hallway-like setting from the participants' point of view

Figure 3-2 hallway-like setting from the robot's point of view
(left blue line: participants' starting position during lateral trials; right blue line: participants' starting position during frontal trials)

3.1.3 Task

In this study, participants were instructed to indicate their arising level of discomfort by remotely stopping the approaching mechanoid or by actively adjusting their own lateral distance towards the passing mechanoid. Thus, during all frontal distance trials subjects were asked to drive the robot towards themselves and stop it as soon as they started to feel uncomfortable without correcting the robots position after the initial stop. With respect to all lateral distance trials, subjects were asked to position themselves along a marked blue 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 during the lateral scenario participants were instructed to start with their own positioning as soon as they initiated the mechanoid's forward movement. However, it was totally up to them whether they wanted to move at all. Moreover, they were briefed that they should spontaneously come to a decision according to their own subjective sensation. The experimental setup is sketched in Figure 3-3 and the two different trials are illustrated in Figure 3-4 and 3-5.

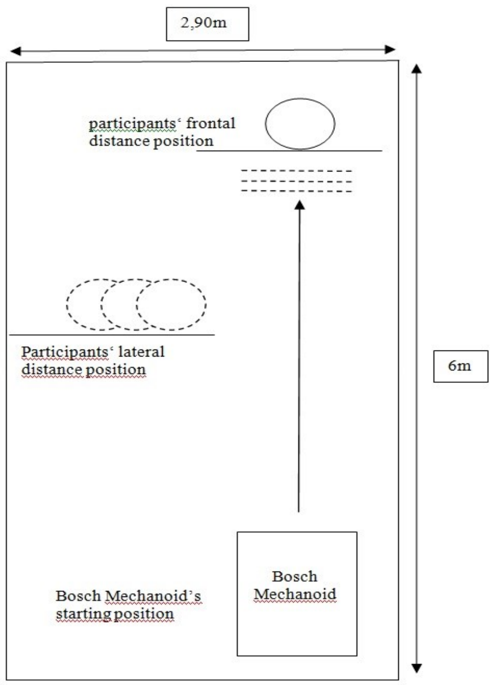

Figure 3-3 experimental setup

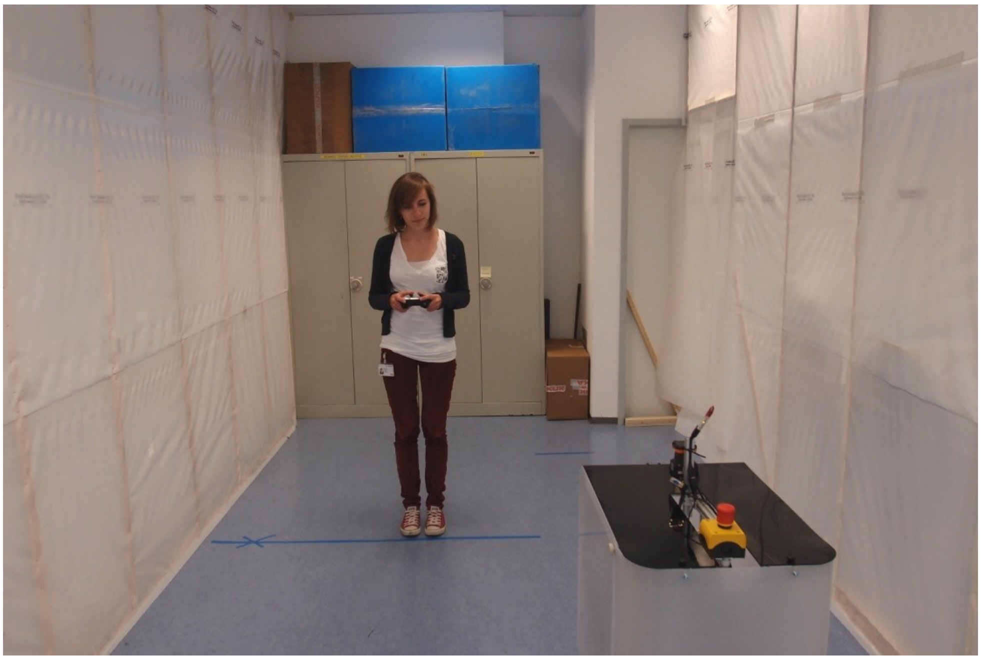

Figure 3-4 screenshot during a lateral trial

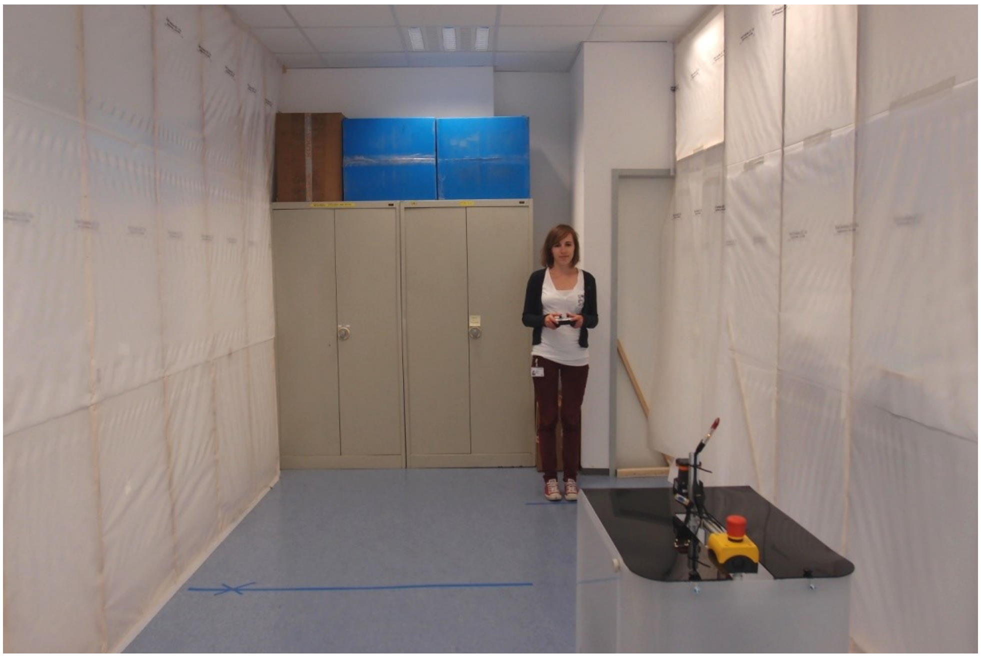

Figure 3-5 screenshot during a frontal trial

3.1.4 Experimental Design

Towards investigating the developed hypotheses, two experimental blocks with a 2x2 within-subject design were conceptualized. The first block examined accepted frontal distances (FD), and the second block examined accepted lateral distances (LD). Both blocks comprised the same two within-subject variables: robot speed (v1 = 0.6m/s and v2 = 0.8m/s) and type of contact (first contact LD1/FD1, second contact LD2/FD2). The selected speeds were based on reviewed findings, conducted pre-tests and technical constraints. Speed values below 0.6m/s have already been reported as less comfortable (Pacchierotti et al., 2005), which was additionally validated by conducted pre-tests. This study aimed to work with speeds that were rather expected to be suitable for a market-ready application and thus, no lower speeds than 0.6m/s were tested. Though it would have been of high interest to test faster speeds than 0.8m/s as well, for instance 1.0m/s, technical constraints of the robot limited the maximum speed to 0.8m/s. The second within-subject variable was chosen in order to increase the reliability of the measured distances as well as to get insights into potential habituation effects.

Thus, each block consisted of four diverse experimental conditions which resulted in eight total trials. All trials were randomized in each experimental block and both blocks were balanced in order to avoid two identical conditions in sequence. All experimental conditions were labeled according to the within-subject factors (LD1_v1 = first exposure to the lateral condition with a robot speed of 0.6m/s; LD2_v2 = second exposure to the lateral condition with a robot speed of 0.8m/s; etc.) As dependent variables, the smallest lateral distance and the smallest frontal distance were assessed.

3.1.5 Procedure

First, subjects were informed about the scope of the study and data privacy. They were also introduced to the mechanoid and were briefed regarding its potential future functionality. A possibly negative association with the term '*robot*', as suggested by Meyer (2011), 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 recording demographical data as well as their prior experience with the used prototype and other autonomous systems (see Appendix I).

Upon instructing participants with the described task and briefing them about the robot's remote control, the main part of the experiment started. Before starting off with the first experimental condition, subjects had to conduct several practice runs (accelerating and decelerating) in order to get familiar with the remote control. Since the participants exclusively had to start and stop the robot, all other control options (e.g. steering, turning sideways, changing speed) were disabled. This resulted in an easy operation of the remote control and was mastered by all participants without any difficulty. Independent of the chosen controller intensity, the robot would always drive at the predetermined speed. In addition, minimized control functions of the robot's motion always led to the same straight forward trajectory. Upon practicing, the examiner drove the mechanoid via remote control to its starting position and the experiment began. Before each trial, the examiner left the laboratory hallway-like setting and remotely adjusted the appropriate speed level of the robot, according to the corresponding experimental condition. The robot was then remotely controlled by the subjects throughout all trials. If the established distance between the subjects and the robot would not have met the subjects' sensations, the trial would have been repeated in order to minimize measurement errors, as proposed by Hayduk (1978). However, this case did not occur in the entire study. 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 next starting position of the subjects depending on the upcoming experimental condition. Subsequently the subjects went on with the next trial.

All in all, subjects had to undertake eight different experimental conditions and the entire experiment lasted approximately 30 minutes.

3.1.6 Distance Measurement Technique

As already introduced in the beginning of this doctoral project, the *'transport assistant'* was equipped with an extra laser range finder which was placed in the body centre on top of the mechanoid's shell. It is essential to highlight again that this relatively high attached laser rage finder (0.97m above ground) was utilized for all distance measurements within this study. It captured the subjects' hips, respectively belly region, which posed a novel distance measurement approach in human-robot proxemics (compare section 2.7.3.5). Recorded laser data was automatically stored in rosbag-files that were subsequently analyzed via a script in MATLAB. Attained minimal lateral as well as frontal distances posed the absolute distance between the center of the laser and the closest point of the participants' belly/hip region. From this measurement, the length or width of the mechanoid's body was subtracted from these obtained minimal distance values in order to assess the distance between the closest body parts of both interacting agents, adhering to the proposed methodological working standard proposed by Walters (2008, p. 175) (compare section 2.7.3.5). By taking into account the utilized laser range finder and its estimated performance, a measurement accuracy of 0.05m was achieved.

3.2 Results

With respect to the assessed dependent variables (accepted frontal and lateral distance), the recorded data of the upper laser range finder is analyzed. An overview of the attained findings is given in Figure 3-6. The illustration includes all computed mean distances and the corresponding standard errors.

LD1 = first lateral distance trial
LD2 = second lateral distance trial
FD1 = first frontal distance trial
FD2 = second frontal distance trial
v1 = 0.6m/s
v2 = 0.8m/s

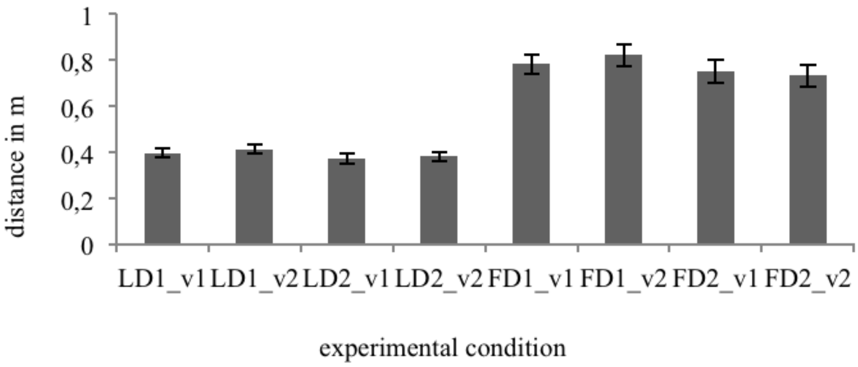

Figure 3-6 means and standard errors of all distance trials

Towards testing the first hypothesis, four 1-sample t-tests (Bortz & Döring, 1995) are computed which examine the difference between the empirically attained frontal distance means and the reviewed threshold of the intimate personal space zone (0.46m). All required preconditions to apply 1-sample t-tests are fulfilled (Rasch, Hofmann, Friese & Naumann, 2010). By adjusting the significance level from $\alpha=0.05$ to $\alpha=0.0125$, the multiple testing problem (cf. Bortz & Döring, 1995) is taken into account. The computed analysis shows that all attained frontal mean distances are significantly greater than 0.46m ($p<0.01$): FD1_v1 ($M=0.78$, $SD=0.26$), 0.46m, $t(34)=7.267$, $p=0.000$ / FD1_v2 ($M=0.82$, $SD=0.28$), 0.46m, $t(34)=7.609$, $p=0.000$ / FD2_v1 ($M=0.75$, $SD=0.29$), 0.46m, $t(34)=5.891$, $p=0.000$ / FD2_v2 ($M=0.73$, $SD=0.27$), 0.46m, $t(34)=5.939$, $p=0.000$.

With respect to the second hypothesis, paired t-tests are computed in order to explore whether significant differences exist between gained frontal and lateral distances. Again, the multiple testing problem (cf. Bortz & Döring, 1995) is considered by adjusting the significance level from $\alpha=0.05$ to $\alpha=0.0125$. All required preconditions to apply paired t-tests are fulfilled (Rasch, Hofmann, Friese & Naumann, 2010). As shown in Table 3-1, significant differences ($p<0.01$) are obtained in the scores among all frontal distance conditions and lateral distance conditions. Each assessed frontal distance is greater than the comparable lateral distance (same type of contact and same level of speed). In addition, the accepted lateral mean distance (M=0.40m, SD=0.125m, SEM=0.02m) and the accepted frontal mean distance (M=0.77m, SD=0.275m, SEM=0.04m) for all trials are assessed. Both means are sketched in Figure 3-7.

Trial	**Mean (M) in m**	**Standard Deviation (SD)**	**t(34)**	**p**
First Time Lateral Distance and 0.6m/s (LD1_v1)	0.39	0.14	-9.932	<0.01
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	<0.01
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	<0.01
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	<0.01
Second Time Frontal Distance and 0.8m/s (FD2_v2)	0.73	0.27		

Table 3-1 significant differences between lateral and frontal trials

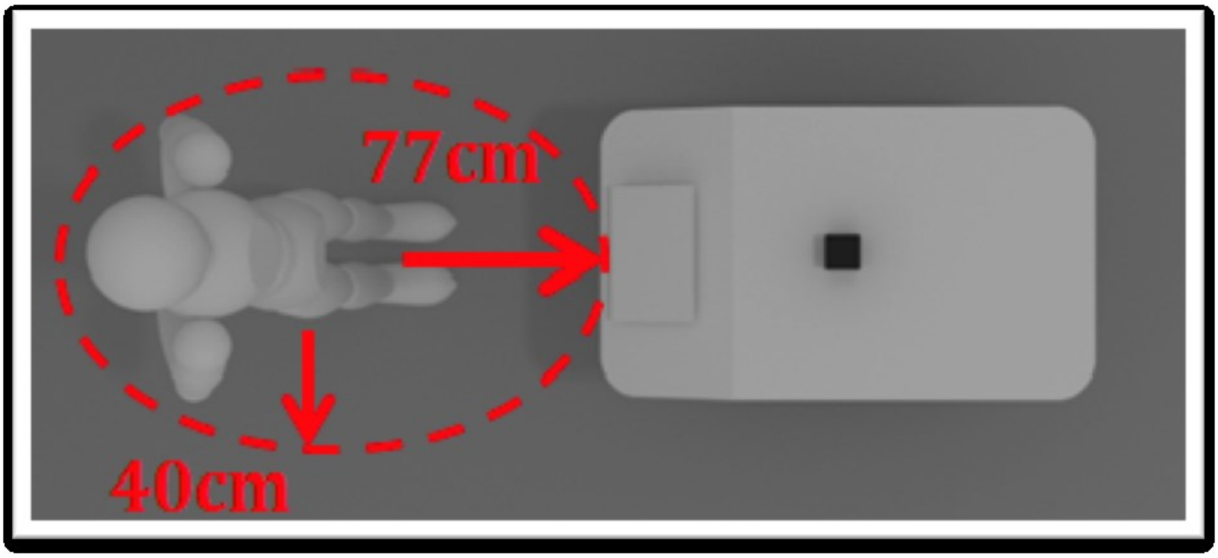

Figure 3-7sketched computed means of accepted frontal and lateral distances

To fathom the third hypothesis, two repeated measures 2-way ANOVAs (Bortz & Döring, 1995) with robot speed and type of contact serving as within–subjects variables, and frontal distance or lateral distance serving as the dependent variable, are computed. The required statistical assumptions (interval-scaled variables, Gaussian distribution, and sphericity, cf. Rasch, Friese, Hofmann & Naumann, 2006) for applying ANOVA are tested and hold true for both dependent variables. Table 3-2 summarizes the attained results and additionally reports the effect size η^2 after Cohen (2013) (small: $0.01 < \eta^2 < 0.08$, medium: $0.08 < \eta^2 < 0.14$, large: $0.14 < \eta^2$).

Independent Variable	**Effect**	**F (df1,df2)**	**p**	**η^2**
Speed (S)	**frontal distance**	**(1,34) = 4.919**	**0.033**	**0.126**
	lateral distance	**(1,34) = 7.132**	**0.012**	**0.173**
Type of contact (TC)	frontal distance	(1,34) = 0.02	0.88	0.00
	lateral distance	(1,34) = 0.409	0.527	0.012
S x TC	frontal distance	(1,34) = 2.686	0.11	0.073
	lateral distance	(1,34) = 0.153	0.698	0.004

Table 3-2 effects for each dependent variable (significant effects are printed in bold)

The analysis shows that a significant main effect ($p \leq 0.05$) occurs for the varied robot speed in both blocks (frontal and lateral distance) while the type of contact does not significantly influence participants' lateral and frontal distance preferences. Furthermore, no significant interaction effect is found. Computed Bonferroni post-hoc comparisons, which take the multiple testing problem into account (Bland & Altman, 1995), show that the accepted frontal and lateral distances significantly increase when the robot drives at speed of 0.8m/s (frontal: $p=0.033$; lateral: $p=0.012$).

In addition, four repeated measures 3-way ANOVAs with robot speed and type of contact serving as within-subjects variables and either one of the control variables (gender, professional background, prior experience with autonomous systems, prior experience with the applied mechanoid) serving as a between-subjects variable are computed for each block (frontal and lateral distance) to test whether one of the control variables significantly influences the assessed distances. As with the previously applied 2-way ANOVAs all required statistical preconditions are fulfilled (Rasch et al., 2006). The analysis shows a significant main effect as well as significant post-hoc tests for gender on subjects' frontal distance preferences. It is observed that male subjects accept significantly smaller frontal distances than female subjects ($p=0.012$) (see Table 3-3). However, a similar gender effect is not observed within lateral distance trials ($p=0.564$). The complete statistical results of the computed 3-way ANOVAs examining a potential influence of gender are shown in Appendix B.

Apart from this finding, the analysis reveals that all further gathered control variables (professional background, prior experience with autonomous systems, and prior experience with the applied mechanoid) do not significantly affect subjects' distance preferences.

Trial	Mean distance male subjects	Mean distance female subjects
FD1_v1	0.68m	0.88m
FD1_v2	0.71m	0.94m
FD2_v1	0.66m	0.84m
FD2_v2	0.61m	0.85m

Table 3-3 assessed frontal mean distances for male and female subjects

Lastly, and most important for this dissertation, cumulative frequency distributions of measured minimal distances are assessed and the charts show very sensitive areas between approximately 0.5m and 1.2m for frontal distances, and between approximately 0.25m and 0.55m for lateral distances. In addition, the resulted frontal distribution is contextualized with the proposed personal space notation system according to Hall (1966). Thus, a close view to the cumulative frequency distribution of frontal distances reveals that an approximate majority of slightly higher than 70% of all participants prefers a minimal frontal distance within the personal zone according to Hall's (1966) categorization (0.46 to 1.22m). By applying the proposed thresholds of the personal zone to the cumulative frequency distribution of frontal distances, it is also obtained that slightly less than 20% of the participants establish distances below 0.46m (intimate zone) and approximately 10% above 1.22m (social zone). Hence, the range containing this majority approximately starts at 20% and ends at 90% of the cumulative frequency distribution. The complete cumulative frequency distribution is charted in Figure 3-8 and the thresholds of the personal zone are marked with red circles. As also depicted in Figure 3-8, all assessed frontal distances approximately range from 0.3m to 1.5m.

As a next step, these gained start and end markers, dividing the attained results according to Hall's (1966) categorization, are taken as a reference and are transferred to the cumulative frequency distribution of lateral distances. Accordingly, an approximate 70% majority of established lateral distances by all participants approximately occurs between 0.25m and 0.55m. Additionally, the following boundaries for a possible lateral zone categorization are derived: zone #1 approximately ranging from 0.0m to 0.25m and containing slightly less than 20% of the established distances, zone #2 approximately ranging from 0.25m to 0.55m and containing 70% of the established distances, and lastly, zone #3 approximately starting at 0.55m and containing 10% of the established distances. This is also illustrated in Figure 3-8 by red circles approximately indicating the thresholds of zone#2. With respect to the lateral scenario, all assessed lateral distances approximately range from 0.15m to 0.75m.

As previously noted, these cumulative frequency distributions constitute a highly relevant empirical base for subsequent autonomous distance evaluations within this dissertation.

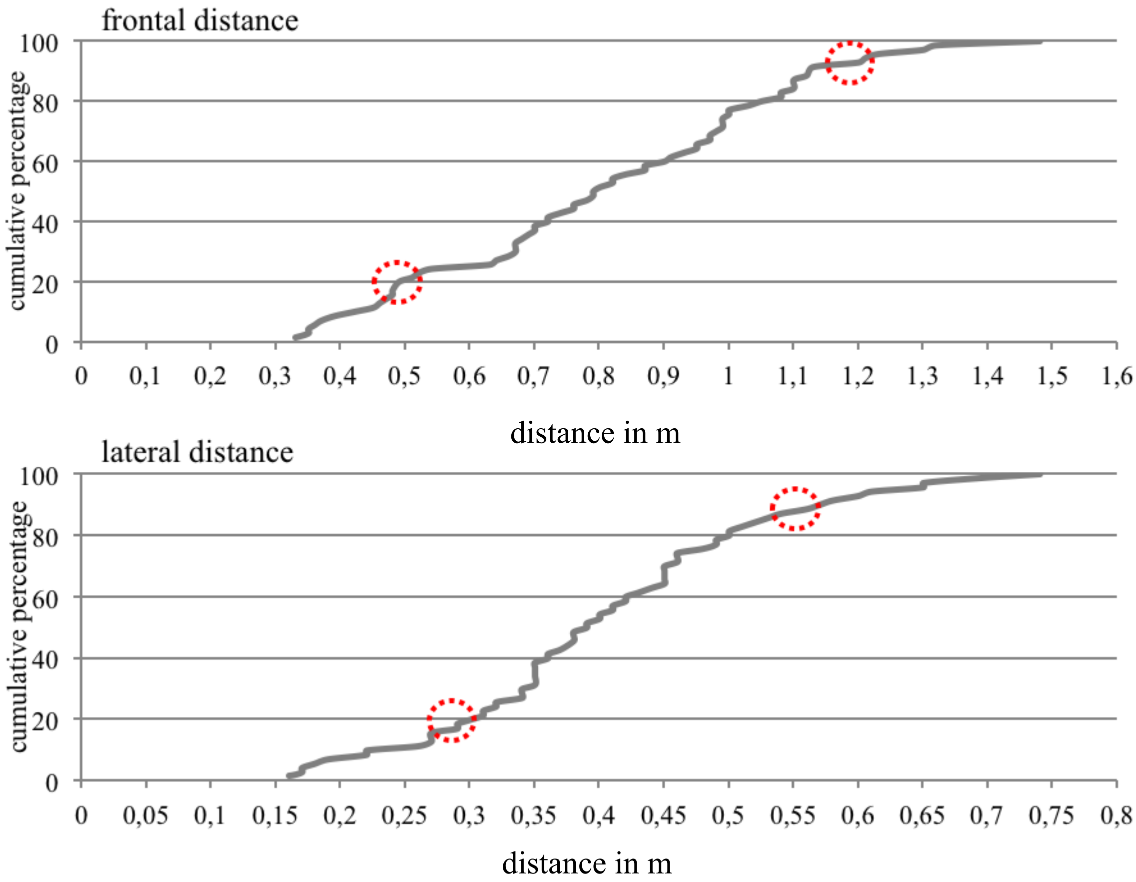

Figure 3-8 frequency distributions of frontal and lateral distances

3.3 Discussion

By putting the participants in control of the mechanoid, the goal of this study is to establish an empirical starting base for further developments of hypotheses in order to support follow-up studies, exploring socially appropriate proxemic behaviour of an autonomously moving robot in a hallway.

To sum up, the present work generally aligns to previous HRP research by providing support for the relevance of an adequate proxemic behavior during a HRSI in a hallway. In particular, indications for accepted frontal (0.77m) and lateral (0.4m) distances are empirically gained, which are crucial for avoiding feelings of discomfort during a HRSI in a hallway. The experiment also shows that the accepted frontal approach mean distance is greater compared to the majority of subjects' frontal distance preferences in previous HRP studies. In addition, the present study provides first insights into a possible categorization of lateral personal space zones. Furthermore, additional indications regarding a significant effect of robot speed and gender on subjects' distance preferences are attained. In contrast to related work, no habituation effects are observed.

In regard to the developed first hypothesis, all gained single frontal distance means are significantly greater than 0.46m. Thus, the assumptions of the first hypothesis are supported. In addition, accepted frontal distances below 0.46m occur for slightly less than 20% of all participants, which has been similarly obtained by Hüttenrauch et al. (2006). In contrast to previous work (Walters et al., 2006; Walters et al., 2008a; Koay et al. 2007; Takayama & Pantofaru, 2009), a greater frontal mean distance is assessed, which may support introduced assumptions from HHP, regarding the effects of spatial density on distance preferences (Dabbs et al., 1973; Hayduk, 1983; Evans and Wener, 2007). In contrast to the reviewed previous HRP studies (e.g. Walters et al., 2006, 2008b), the present examination took place in a denser environment. Possibly, this finding also indicates that a rather cubic-like outward robot design leads to greater frontal robot-to-human distance preferences than less bulky designed mechanoids (e.g. PeopleBot). Suggestions for this assumption have been revealed by HHP research, reporting that a more voluminous body size leads to greater interpersonal distances due to a higher level of induced threat.

Nonetheless, in sum, the present results support previous postulations, suggesting the personal zone as the most suitable for frontal robot-to-human approach maneuvers (Hüttenrauch et al., 2006; Brandl et al., 2013). Along this line of argumentation, it can be assumed that the frontal distance preference indicates that subjects perceive the robot as a social actor, but not in a way similar to a lover or close family member (intimate zone). However, it remains questionable whether the associated human-human types of relationships with personal space zones can be transferred to human-mechanoid relations, and additionally, whether the suggested relationships have anything to do with the observed distances. As already expounded in the theoretical foundation, humans may treat robots in a social way and therefore, certain social conventions and concepts of HHI, such as proxemics, are also relevant in HRI. Nonetheless, robots are not seen as a social entity identical to a human (e.g. Dautenhahn, 2007). Thus, suggested personal space zones and their reflection of specific types of human-human relationships may not be valid for a HRSI. In addition, suggested relationships by Hall (1966) apply for direct interaction scenarios, such as conversations. The present study, however, exclusively simulated an approaching or passing by maneuver in a hallway without any direct interaction (verbal or physical) involved. Thus, a potential transfer of those assumptions (Hall, 1966) to the present context also lacks comparability. Therefore, it remains open whether participants rather tend to treat a social service robot as a friend than as a lover or family member, or rather as a type of social servant than a machine, or as anything like that at all. Future studies could potentially investigate this subject by evaluating people's perceived relationship to robots and by running long-term studies that examine a potentially changing human-robot relationship over time.

Taken together, attained findings indicate the existence of a frontal threshold of comfort (= accepted frontal mean distance). Due to its mobile and embodied character subjects probably perceive a certain degree of threat towards the approaching robot, resulting in a minimally accepted distance. Similar to an approaching human or animal, the risk of a potentially crash is prevalent in this sort of scenario, which in turn induces threat and causes minimally accepted distances. Accordingly, given the machine-like character of the robot (no head or eyes for mutual gaze behavior), and a constant degree of locus-of-control, the *Dosey-Meysels Protection Theory* (Dosey & Meisels, 1969) seems to be most suitable to the examined context, as already observed in HHP.

With respect to the second hypothesis, the scores of accepted frontal mean distances are significantly higher than accepted lateral mean distances throughout all experimental trials. In particular, all assessed frontal mean distances are almost twice as big as assessed lateral mean distances. Thus, these findings provide support for the second hypothesis. Furthermore, this experiment poses the first systematic exploration of accepted lateral distances towards a passing robot in a hallway. An attained lateral mean distance of 0.4m is in accordance with initial indications from Pacchierotti et al. (2006), and unveils that a lateral spatial threshold of comfort (= accepted lateral mean distance) exists as well. Interestingly, though the study of Pacchierotti et al. (2006) has explored a complete avoidance scenario, the more bulky appearance of the transport assistant does not seem to evoke greater lateral passing preferences compared to the less bulky PeopleBot. Presumably, a passing by scenario will not induce a crash threat among participants compared to a frontal approach scenario which does tend to threaten a potential collision course. In regard to the proposed egg shape of personal space (see section 2.7.1), this experiment provides a first empirical evidence, supporting this assumption within human-robot proxemics. However, this finding only poses an initial indication. Future studies should also address robot-to-human approaches from the side, such as in previous HHP studies (e.g. Ashton & Shaw, 1980).

With respect to a lateral zone categorization, initial indications are derived from stated findings. By transferring the obtained percentages of the personal space zones from the frontal distance distribution to the lateral one, the distribution can be divided into zone#1, #2, and #3. Corresponding distance ranges are obtained and show that the majority (>70%) of selected lateral distances occur in the range between 0.25m and 0.55m. Assuming that the lateral distribution of personal space zones approximately aligns to the frontal one, it can be hypothesized that zone#2 reflects the dimensions of a lateral personal zone. Along this line of argumentation it can be further presumed that a possible quantification of an intimate zone (or zone #1) for lateral distances ranges from 0.0m to 0.25m, and that a lateral social zone (or zone #3) starts at 0.55m. Though this study sheds a first light on an exploration of lateral spatial zones, these findings can only be interpreted as a first starting point in an iterative process of future studies, focusing on the exploration of lateral personal space zones.

At this point one can summarize that the employed robot should respect frontal and lateral spatial thresholds of comfort in a hallway, i.e. it should avoid an invasion of subjects' personal space in order to show a comfortable proxemic behavior. In line with previous findings (e.g. Walters, 2008; Brandl et al., 2013), the general relevance of human-robot proxemics is additionally supported by this study, but gained frontal mean distances are greater compared to many previous studies. It is assumed that this result occurs due to a higher spatial density of the test environment (hallway). In addition, gained mean thresholds (frontal: 0.77m, lateral: 0.4m) provide an empirical starting base to develop further hypotheses, addressing an acceptable proxemic behavior of an autonomously approaching or passing mechanoid in a hallway.

With respect to the third hypothesis, the analysis shows that a faster robot speed significantly increases the accepted frontal and lateral mean distances. Thus, the third hypothesis is supported and this finding is in line with reviewed previous research that has indicated an interaction of speed and comfortable distances (e.g. Mizoguchi et al., 2007; Brandl et al., 2013). Attained findings in the present study show a significant influence of an increased robot speed by 0.2m/s on distance preferences. Though the tested robot speeds in the experiment of Brandl et al. (2013) were different (0.25m/s; 0.5m/s; 0.75m/s), the present study indicates that even smaller speed variations than 0.25m/s lead to significant changes in people's perception of spatial comfort. Future research should investigate whether this effect also occurs for even smaller variations in robot speed (e.g. 0.1m/s) and whether it can be observed for different levels of speed (e.g. 1.0m/s). Unfortunately, no faster robot speed than 0.8m/s could be consistently realized due to technical constraints in this experiment, but it should be subject of investigation in future studies. As already indicated by previous work (e.g. Pacchierotti et al., 2005; Dautenhahn et al., 2006), slower robot speeds than 0.6m/s have been perceived as less comfortable and therefore were not considered in the present experiment. However, a slower robot speed than 0.6m/s could be advantageous for very narrow or dense environments in order to permit a closer HRSI. Furthermore, the assessed difference in subjects' distance preferences due to the varied robot speed is relatively small (<0.05m), which might pose a further relevant practical benefit. It might be advantageous for software and hardware engineers to have a higher level of design flexibility regarding behavioral realizations of robots. For instance, both employed mechanoids in this project drove significantly more accurate and were expected to be less affected by technical problems at a speed of 0.6m/s. Accordingly, those technical limitations can be taken into account without requiring a completely altered proxemic behavior. On the other hand, potential advantages of faster robot speeds (e.g. for a domestic security robot that needs to drive fast) might be applicable as well without causing resource-consuming changes in a robot's acceptable proxemic behavior. In sum, this finding additionally highlights, like previous research, the significant impact of robot speed on people's spatial comfort and roboticists should consider this effect when designing future software patterns.

With respect to the type of contact (first/second), results show that the repetition of trials has no significant influence on subjects' distance preferences in the present experiment. Surprisingly, this finding is not in line with previous research, which has shown that significant habituation effects already occur upon the first contact (Walters et al., 2011). On the other hand, Koay et al. (2007) have observed significant decreases in subjects' distance preferences upon a third exposure. Unfortunately, the design of the present study only permits insights into potential habituation effects upon a second exposure with the robot. Therefore, future studies, investigating HRSI over more than two exposures, should be conducted in order to shed light on the power of habituation and its impacts on distance preferences. Since it is impossible for a robot to capture an unknown person's degree of habituation by a sensor, gathering insights into habituation effects of diverse target populations would be helpful for adapting the robotic behavior to a specific environment. However, though there is empirical evidence that has shown significant influence of habituation on people's distance preferences (e.g. Koay et al., 2007; Takayama & Pantofaru, 2009; Walters et al., 2011), a well-designed first contact is also pertinent (Koay et al., 2007; Bartneck et al, 2009b). In sum, this study rather suggests support for previous findings from Koay et al. (2007) by showing that subjects' distance preferences are not significantly influenced due to a second exposure to the robot. However, study details like duration and type of interaction are different compared to previous research and might influence the potential power of habituation. Thus, future studies should be conducted to examine this subject.

In regard to the next finding, the significant gender effect poses an empirical support to previously gathered findings in HHP. As noted in the theoretical foundation of this dissertation (see section 2.7.2), though a rather inconclusive body of knowledge prevails, gender influences on personal space have been already postulated in HHP (Sobel & Lillith, 1975). Research in HHP has shown that women tend to maintain greater frontal distances compared to men (Sobel & Lillith, 1975), which is also suggested for a HRP context in the present experiment. However, this effect is not observed in lateral trials, which may occur due to a generally lower level of induced threat in lateral scenarios.

Lastly, this experiment introduces a novel methodological approach within HRP studies. As previously expounded in the theoretical part (see section 2.7.3.5), HRP is in essential need of working standards in order to increase the comparability among diverse studies. Walters (2008, p.175) has proposed a standard regarding the start and end point of the measured distance between interacting agents. Walters (2008) has suggested to take the distance between the nearest opposing static body parts, excluding manipulators such as arms and legs. However, he and his colleagues took the participants' feet as a reference point. In regard to proposed effects of body size (Lerner, 1973; Sommer, 2002a), closest body parts strongly depend on the biometrics of a human. Therefore, this working standard is differently applied by relying laser measurements on the participants' hips/belly region. In addition, the robot's on-board sensors are used for the distance assessment, which is beneficial in terms of data accuracy compared to formerly applied methods, such as grids or metric scales on the floor (e.g. Walters et al., 2006). Furthermore, visible metric scales on the floor have been proposed to influence participants, which are avoided by the present measurement design (Walters, 2008).

In addition, previous work has been primarily based on an examiner's confederate who stopped the robot upon receiving participants' indications of discomfort (Walters et al., 2006). Alternatively, Comfort Level Devices have been applied (e.g. Koay et al., 2007), or participants verbal stop indications have been recorded and subsequently been analyzed by using video data (e.g. Walters et al., 2006). The applied method in the present study is seen as beneficial because it avoids biased distance assessments caused by latency effects and is more efficient compared to subsequent video analysis. Furthermore, experiments using Comfort Level Devices have biased the results by limiting the maximum frontal approach distance of the robot due to safety constraints.

Nonetheless, it remains inconclusive whether humans control robots according to their expectations towards robots or towards their own underlying understanding of spatial behavior in the specific context. Thus, methods comprising humans that actively control robots are not necessarily valid for gaining insights into people's expectations towards autonomously moving robots.

3.4 Conclusion

With respect to theoretical and practical implications, one main conclusion needs to be highlighted: Roboticists should be aware of prevailing frontal and lateral spatial thresholds of comfort that a socially acceptable approaching or passing robot in a hallway should not overshoot. By integrating these thresholds into future software frameworks, it can be assumed that large portions of disaffected humans in robots' proximities can be avoided. In addition to the accepted mean distances, the study shows that these distances significantly increase due to a faster robot speed. However, the present study exclusively examines people's distance preferences by putting the robot in control of the participants, which will not apply to future real-world applications. Therefore, attained findings exclusively serve as an empirical foundation for successive hypotheses and investigations of comparable scenarios with autonomous robots.

4 Study II: Exploration of Accepted Distances Toward an Autonomously Approaching and Passing Mechanoid (Transport Assistant) in a Hallway

This follow-up study primarily aims to validate previously attained distances for an autonomously moving mechanoid (transport assistant). In particular, accepted frontal and lateral mean distances toward an autonomously moving transport assistant in the same hallway-like setting are systematically evaluated. In contrast to the first study, the mechanoid is autonomously approaching and passing a standing participant. Hence, in this experiment, the subjects are not in control of the mechanoid.

In addition, the present study aims to explore the potential influence of diversely maintained frontal and lateral distances on the overall motion acceptance of the mechanoid.

In sum, this examination answers the following three research questions:

1. Which frontal distance does a standing person accept from an autonomously approaching mechanoid (transport assistant) in a hallway?

2. Which lateral distance does a standing person accept from an autonomously passing mechanoid (transport assistant) in a hallway?

3. Does the distance behavior of an autonomously moving mechanoid (transport assistant) affect the motion acceptance of this robot?

Based on empirically gained mean distances in the first study, it is assumed that an autonomously approaching or passing mechanoid should consider these distances as well. Furthermore, as previously outlined in the theoretical foundation, proxemics poses a relevant feature of human and robotic motion behavior (Birdwhistell, 1952; Hall, 1973; Brinker et al., 2000; Walters, Dautenhahn, Te Boekhorst, Koay, Syrdal & Nehaniv, 2009) and is therefore expected to affect the overall motion acceptance of a robot. In addition, Mori (1970) proclaimed that *'... it is possible to create a safe familiarity with a non-humanlike design'*. Though Mori (1970) has not provided any empirical proof, he has proposed that by designing similar levels of human motion features for a machine-like looking robot, the overall familiarity increases, which has been generally confirmed by a series of experiments in HRI (e.g. Kanda et al., 2007). However, as reviewed in the theoretical foundation, it has remained very uncertain whether familiarity or another concept, such as acceptance, might be a more appropriate assessment (Bartneck et al., 2009a; von der Pütten and Krämer, 2012). Since familiarity has been questioned to be equivalently translatable from Japanese (Bartneck et al., 2009a), the present work measures acceptance, which is specified to the prevailing research context, resulting in motion acceptance.

Consequently, the following predictions were derived for the present study:

Hypothesis I: *The accepted frontal mean distance toward an autonomously approaching transport assistant in a hallway corresponds to the assessed frontal mean distance in the first study.*

Hypothesis II: *The accepted lateral mean distance toward an autonomously passing transport assistant in a hallway corresponds to the assessed lateral mean distance in the first study.*

Hypothesis III: *Maintained distances that correspond to the previously assessed mean distances in the first study positively affect the overall motion acceptance of an autonomous transport assistant in a hallway opposed to smaller distances. In addition, maintained distances that exceed the previously assessed mean distances in the first study lead to a higher motion acceptance.*

4.1 Method

In order to achieve a high comparability with the first study, it was substantial to design this follow-up study as similar as possible. Accordingly, multiple study details regarding the utilized mechanoid, experimental setting and sample characteristics were as much aligned as possible to previous circumstances.

4.1.1 Participants

Altogether, 40 participants took part in the study and none of them had participated in the first study. The 20 male and 20 female subjects had an average age of 29.2 years (SD = 5.81). Most participants were Germans (n = 38 / 95%), followed by 1 Pole and 1 Greek, and rather had a non-technical professional background (n = 27 / 67.5%) opposed to 13 subjects with a technical background (32.5%). With respect to the prior experience with autonomous systems, 31 (77.5%) participants indicated no prior experience whereby the rest were somewhat familiar with autonomous vacuum cleaners and lawn mowers. In accordance with the first study, most participants had not seen the applied mechanoid before (75%). Again, all participants received a 30€ voucher for their participation.

Basic sample characteristics such as gender, age, cultural background and prior robotic experience were very similar to the first study. In order to compare the sample characteristics, unpaired t-tests were computed and results are presented in Appendix C.

4.1.2 Material

As already noted in the preface of this subchapter, the majority of the utilized material of the present study did not differ from the first study. In sum, the identical laboratory hallway-like setting and the identical mechanoid (*transport assistant*) were applied (see section 3.1.2). In addition, a small round table and a chair were placed in the rear left corner of the hallway (from the mechanoid's point of view). Its position is shown in Figure 4-1.

Figure 4-1 additional table in the hallway-like setting

The table was provided for completing all questionnaires by the participants, and the chair was used by the examiner to put off additional material, such as an iPad and a Gamepad. As in the first study, the same Logitech wireless Gamepad was used. It served the examiner to manually maneuver the mechanoid into the hallway and to its starting position after each trial. The iPad was needed for launching the autonomous movements of the mechanoid which is subsequently explained in greater detail. Diverse other study details, such as the metric dimensions of the hallway, participants' frontal and lateral starting positions, the mechanoid's starting position, its technical specification (e.g. acceleration) and its physical appearance were identical to the first study (see section 3.1.2). Lastly, it is relevant to note that during all experimental trials the mechanoid drove with a constant speed of 0.6m/s. This value guaranteed a significantly higher accuracy of the maintained distances and was therefore favored over 0.8m/s.

4.1.3 Task

Participants received a different instruction compared to the first study. In this experiment, subjects were not in control of the mechanoid. Therefore, they were requested to exclusively observe the autonomously approaching or passing mechanoid without changing their own position. Upon each trial, they were asked to complete a questionnaire, assessing their subjective perceptions and feelings. Participants were instructed to spontaneously indicate their sensations towards the experienced proxemic behavior of the mechanoid. In addition, the instruction highlighted that neither false nor correct answers existed. The instruction sheet is shown in Appendix D.

4.1.4 Experimental Design

In order to explore subjects' sensations towards autonomously maintained frontal and lateral distances, two experimental blocks were conceptualized. Both blocks contained one within-subject variable, respectively. In the first block, the frontal distance was varied across all participants and contained five factor levels (frontal distance: 0.5m/0.65m/0.8m/0.95m/1.1m). Accordingly, in the second block, the lateral distance served as the within-subject variable, also comprising five factor levels (lateral distance: 0.2m/0.3m/0.4m/0.5m/0.6m). The resulting 10 experimental trials were completely randomized in order. This design aimed to take already proven habituation effects into account.

By applying a questionnaire after each trial, the following dependent variables were assessed: the perceived proximity of the mechanoid, the perceived spatial discomfort, the perceived motion acceptance, the expectation conformity of the mechanoid's motion behavior, the perceived safety around the mechanoid, the perceived human likeness of the mechanoid's motion behavior, and the perceived proximity of the mechanoid compared to a human.

A variation of robot speed was not conducted in order to keep the experimental duration at a maximum of one hour.

4.1.5 Derivation of Distance Intervals

All selected autonomously maintained distance variations were based on the attained empirical data of the first study (see section 3.2). In particular, the chosen distance intervals of the present study refer to the attained mean distances and their corresponding standard deviations. In addition, the cumulative frequency distributions were analyzed.

By considering an attained measurement accuracy of 0.05m of the self-controlled frontal mean threshold of comfort (0.77m), the corresponding autonomously maintained frontal distance was rounded up. Thus, 0.8m approximately equaled the empirically gained frontal mean threshold. In regard to this threshold, a variance of 0.27m (standard deviation) was assessed, which was also rounded up. Thus, a large portion of empirically observed frontal distances varied within the range from approximately 0.5m (M – SD) to 1.1m (M + SD). This was additionally corroborated by the reported cumulative frequency distribution which exclusively showed minor percentages below (< 20%) or beyond (~10%) these distances (see section 3.2). Thus, these three distance values posed a reasonable minimum, mean, and maximum distance for the present study. In order to achieve a finer graduation among tested distances 0.65m (M – SD/2) and 0.95m (M + SD/2) were additionally added.

With respect to lateral distances, a similar approach was pursued. A computed standard deviation of 0.12m of the lateral mean threshold (M = 0.4m) was rounded down. Thus, the approximate range from 0.3m (M – SD) to 0.5m (M + SD) led to a large portion of minimally established lateral distances. The cumulative frequency distribution revealed additional support, showing minor percentages below (< 20%) and beyond (~10%) these distances. Thus, these three distances were chosen as reasonable test values. However, they already posed a sufficiently fine graduation (0.1m). In order to expand the test range, 0.2m (M – 2xSD) and 0.6m (M + 2xSD) were selected as a minimum and maximum.

4.1.6 Autonomous Distance Regulation Technique

As already emphasized, the novelty of this study involved the experimental exposure of an autonomous mechanoid to participants. In line with a potential real-world application, participants were not in control of the mechanoid during the experiment. Thus, they could not influence its distance behavior. However, the autonomous proxemic behavior of the utilized mechanoid was simulated. Before the actual experiment, each distance variation was manually driven by the examiner and the precise motion details (e.g. odometry) were recorded and stored in ROS bagfiles. These bagfiles were then launched during the experiment by using a graphical user interface on an iPad. With respect to lateral trials, only one trajectory had to be recorded for all lateral trials. As in the first experiment, lateral distances were adjusted by altering the participants' positions, which is described in the next paragraph. In regard to frontal trials, five diverse trajectories were recorded prior to the experiment. The preparation of all these motion trajectories required several runs in order to accurately maintain the required distances. By applying this technique an accuracy of 0.05m during the experiment was achieved, which was significantly higher than a presumed accuracy of 0.15m by an autonomous distance regulation based on the laser range finder. Furthermore, pre-tests revealed that the autonomous localization of the mechanoid led to long delays in initializing movements, interrupted movements or even caused random turnings. This was avoided by using the above described pre-recorded motion trajectories. Thus, the experimental conduction was less time-consuming and significantly more consistent. Importantly, none of the participants noticed the simulated autonomy.

In regard to lateral trials, the attained empirical data from the first study was assessed by the upper laser scanner of the mechanoid. Thus, the measured closest human body part was the belly/hip region, which was taken into account in the present experiment by adjusting participants' position according to their biometrics of the belly/hip region. Before all frontal trials, the examiner placed a long stick vertically on the blue line which had been taken as the imaginary closest body part during the pre-recordings. Participants were asked to place themselves such that they touched the stick with their belly. Subsequently, they were instructed to hold that position. A similar method was applied for all lateral trials. The blue line was prepared with nearly invisible grey markings at 0.2m/0.3m/0.4m/0.5m/0.6m from the passing mechanoid. These distances had been accurately assessed before the experiment by placing the mechanoid right next to the lateral position. Before an upcoming lateral trial, the examiner placed the stick on the appropriate marking and asked the participants to stand such that they touched the stick with their left hip. Again, participants were told to hold these positions. As in the first experiment, all maintained distances were based on the closest parts of the mechanoid's shell.

4.1.7 Questionnaire

Upon each experimental trial, a questionnaire was handed to the participants assessing all dependent variables. This subsection provides a detailed description of the items and scale levels.

First, the perceived frontal and lateral proximity of the autonomous mechanoid was assessed by one item. Participants could either indicate a *not too close* distance or a *too close* distance. Since a violation of personal space is particularly relevant for the perceived level of comfort, the *too close* dimension was broken down to 4 possible intervals, increasing in their intensity from *a bit too close* to *way too close*. In addition to this item, the questionnaire also assessed the perceived level of spatial discomfort of the subjects. This item comprised a 5-point Likert scale (cf. Likert, 1932) ranging from 1 = not at all, 2 = barely, 3 = neutral, 4 = a bit, to 5 = very.

Second, 6 items were selected to assess the perceived motion acceptance of the mechanoid. As depicted in section 2.7.3.6, acceptance is a crucial metric to assess the quality of human-robot interactions (Lohse & Hanheide, 2008). However, to date, no standardized measurement tool, assessing the motion acceptance of a robot has been elaborated yet. By focusing on the motion acceptance, this methodological approach aimed to assess the contribution of proxemic behavior to an acceptably moving mechanoid in a hallway. The review of existing social acceptance questionnaires constituted the framework for the elaborated items of the present motion acceptance questionnaire. However, these items were in need of adaption to the present explorative context and had been evaluated in a pretest prior to this experiment with 20 subjects. The finally applied items show a high sensitivity and relatively small variance in order to assess motion acceptance in the present context. In detail, six items were divided into three positively poled (*The motion behavior was good, predictable, trustful*), and three negatively poled ones (*The motion behavior made me feel uncomfortable, was strange, was surprising*). For all six items a 5-point Likert scale was employed again. Responses ranged from 1 = strongly disagree, 2 = slightly disagree, 3 = neutral, 4 = slightly agree, to 5 = strongly agree. In regard to the analysis, negatively poled items were re-coded and an overall mean comprising all six items was computed.

Third, additional items addressed the participants' perceived level of safety around the mechanoid, the perceived human likeness of the experienced motion behavior (responses 1 = not at all to 5 = very), and whether the mechanoid's motion behavior met subjects' expectations (responses 1 = strongly disagree to 5 = strongly agree).

Lastly, one item was conceptualized to compare the experienced distance behavior of the mechanoid with commonly behaving humans in the same situation. Responses of this item comprised -2 = way closer, -1 = barely closer, 0 = similar to a human, 1 = a bit farther, 2 = way farther.

In total, two similar questionnaires were used. They exclusively differed in the required phrasing for frontal or lateral trials. A complete version of both original questionnaires in German (frontal and lateral) is attached in Appendix E. The questionnaires also contained an additional item assessing the perceived politeness of the mechanoid's motion behavior. However, this item was not relevant for the present work and was exclusively captured for internal project issues.

4.1.8 Procedure

The experiment started off by introducing participants to the autonomous assistant, data security issues and the scope of the study. After signing a consent form, subjects received a preliminary questionnaire (see Appendix J) and a written instruction that explained the task and upcoming procedure. It was also mentioned in the instruction that the examiner can intervene during the autonomous behavior of the mechanoid at any time. In addition, the examiner emphasized that the participants should base their individual sensations on the autonomously maintained distances. Upon entering the hallway, the examiner repeated the task again and remotely positioned the mechanoid on its starting position. The examiner also remotely controlled the mechanoid upon each trial in order to reposition it to the starting position. Participants were told that this method saves a considerable amount of time than permitting the mechanoid to autonomously drive back. Participants were not briefed about the semi-autonomous proxemic behavior of the mechanoid. As soon as participants had no more questions, the examiner asked them to adjust their first position and subsequently launched the first pre-recorded motion pattern. During the experimental exposure, the examiner backed off and waited at the table behind the participants back. Overall, subjects were exposed to 10 diverse trials followed by 10 questionnaires. The entire experimental procedure lasted for approximately one hour. Figure 4-2 and Figure 4-3 present screenshots from a participant experiencing a frontal and a lateral trial.

Figure 4-2 screenshot of a frontal trial

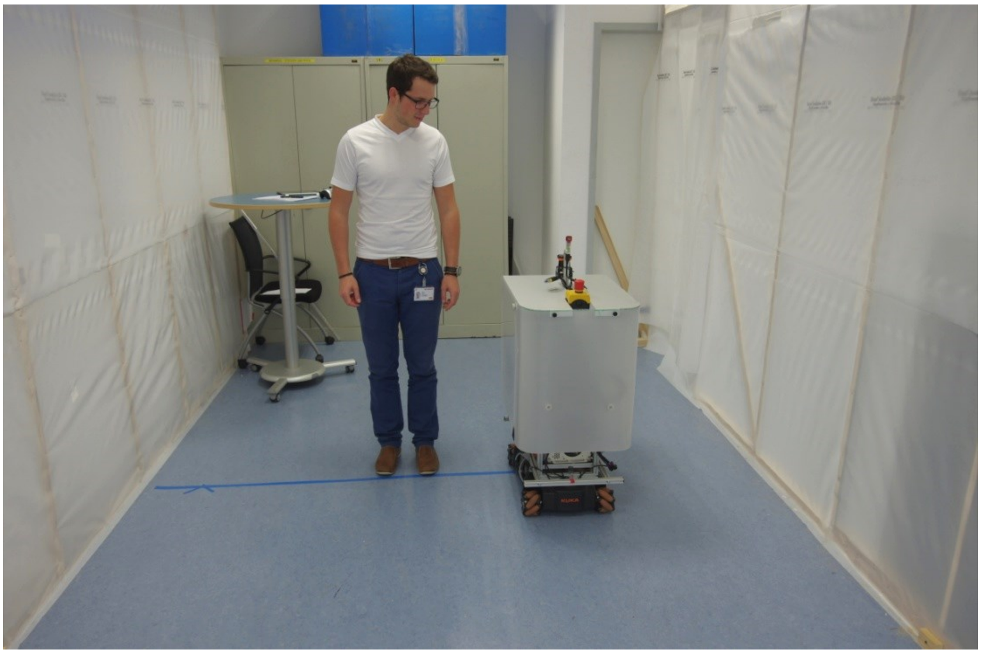

Figure 4-3 screenshot of a lateral trial

4.2 Results

In order to assess the effects of the frontal and lateral distances two repeated measures one-way MANOVAs (Bortz & Döring, 1995), one for each block, are computed. Required statistical assumptions (interval-scaled variables, Gaussian distribution, and sphericity, cf. Rasch et al., 2006) for applying MANOVA are tested and hold true for most dependent variables. Assumptions are exclusively violated for the perceived proximity and the perceived spatial discomfort. However, it has been stated in literature that a violation of these assumptions can be tolerated when working with rather large sample sizes ($N > 10$) (Bortz & Döring, 1995). Thus, for these two dependent variables the Geisser and Greenhouse correction is applied (Bortz & Döring, 1995). Table 4-1 summarizes the attained results and additionally reports the effect size η^2 after Cohen (2013) (small: $0.01 < \eta^2 < 0.08$, medium: $0.08 < \eta^2 < 0.14$, large: $0.14 < \eta^2$).

Dependent Variable	**Distance (IV)**	**F (df1,df2)**	**p**	**η²**
perceived proximity	frontal distance	(3.16,39) = 53.71	<0.01	0.58
	lateral distance	(3.19,39) = 46.56	<0.01	0.54
perceived spatial discomfort	frontal distance	(3.33,39) = 37.86	<0.01	0.49
	lateral distance	(3.19,39) = 36.30	<0.01	0.48
perceived motion acceptance	frontal distance	(4,39) = 16.45	<0.01	0.30
	lateral distance	(4,39) = 19.16	<0.01	0.33
expectation conformity	frontal distance	(4,39) = 5.84	<0.01	0.13
	lateral distance	(4,39) = 10.14	<0.01	0.21
perceived safety	frontal	(4,39) = 13.56	<0.01	0.26

	distance			
	lateral distance	(4,39) = 18.17	<0.01	0.32
perceived human likeness	frontal distance	(4,39) = 6.71	<0.01	0.14
	lateral distance	(4,39) = 13.77	<0.01	0.26
perceived proximity compared to a human	frontal distance	(4,39) = 38.15	<0.01	0.49
	lateral distance	(4,39) = 33.27	<0.01	0.46

Table 4-1 effects for each dependent variable

Due to the non-interval scale level of the perceived proximity, two additional Friedman ANOVAs for frontal and lateral distances are computed. The Friedman ANOVA for the perceived proximity ratings of lateral distances reveals a Chi-square value of 88.87 which is highly significant ($p<0.01$). For frontal distances, the Friedman ANOVA reveals a Chi-square value of 96.83 which is also highly significant ($p<0.01$). Thus, the above mentioned statistical decisions are supported.

In addition, obtained mean scores and standard errors are visualized in Figure 4-4 to 10. Figure 4-4 shows attained results regarding the perceived lateral and frontal proximity of the mechanoid.

How would you rate the autonomous assistant's maintained frontal/lateral distance towards you?

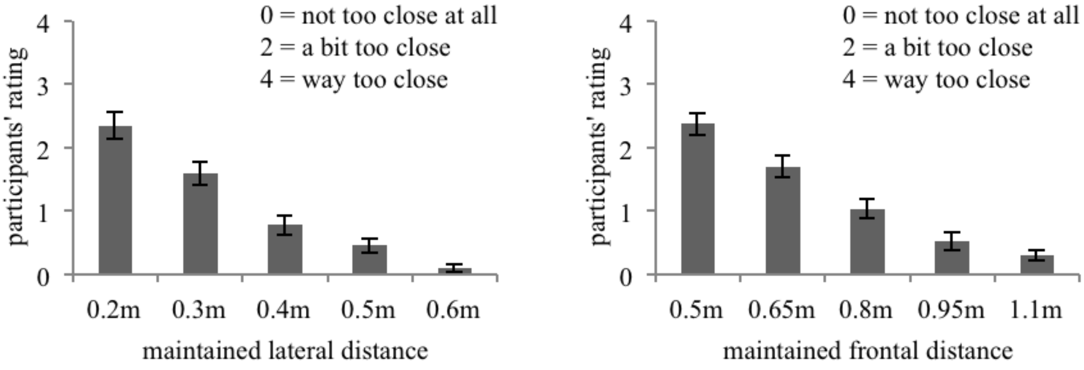

Figure 4-4 illustration of the perceived lateral and frontal proximity

Smaller lateral and frontal distances are rather perceived as way too close compared to greater distances. For determining which means differed from each other, Bonferroni post-hoc comparisons are computed (Bland & Altman, 1995). For lateral distances, post-hoc tests indicate significant differences between all mean scores ($p \leq 0.05$).

Among frontal distances, all single mean scores significantly differ from each other except 0.95m/1.1m. Furthermore, frequencies of '*not to close at all*' ratings for lateral and frontal distances are reported in Table 4-2 and 4-3.

	Lateral Distances				
	0.2m	0.3m	0.4m	0.5m	0.6m
***'not too close at all'* ratings**	6	11	22	28	37
percentage	15%	27,5%	55%	70%	92,5%

Table 4-2 frequencies of not too close at all ratings for lateral distances

	Frontal Distances				
	0.5m	0.65m	0.8m	0.95m	1.1m
***'not too close at all'* ratings**	3	8	15	27	30
percentage	7,5%	20%	37,5%	67,5%	75%

Table 4-3 frequencies of not too close at all ratings for frontal distances

Figure 4-5 depicts the perceived spatial discomfort ratings for lateral and frontal distances. Both obtained main effects reveal that participants' level of perceived spatial discomfort increases the closer the mechanoid passes by or stops in front of them. Post-hoc comparisons indicate significant differences among all mean scores of lateral distance variations except between 0.3m and 0.4m.

For frontal distances, no significant differences occur for 0.5m/0.65m and 0.95m/1.1m.

Did the chosen distance from the autonomous assistant make you feel uncomfortable?

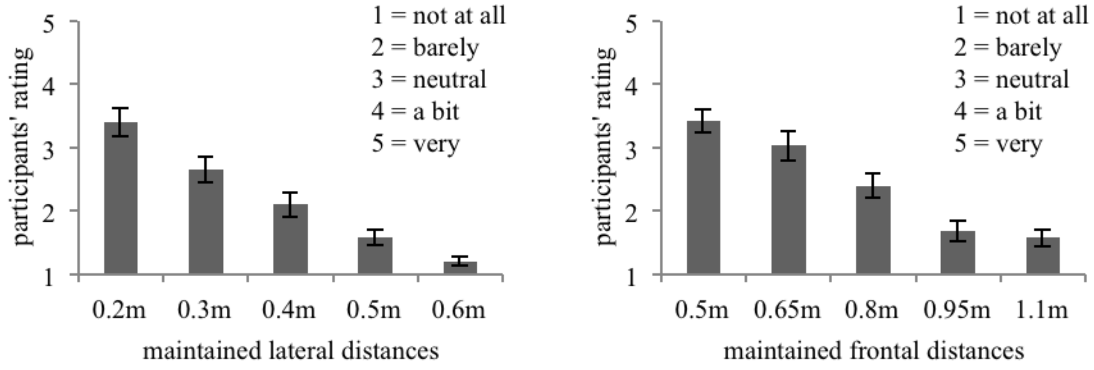

Figure 4-5 illustration of the perceived spatial discomfort for lateral and frontal distances

The assessed motion acceptance ratings for lateral and frontal distances are presented in Figure 4-6. Negatively poled items are re-coded and an overall mean comprising all six items is computed. Internal consistencies of $\alpha > 0.8$ are achieved for lateral and frontal distances. A Cronbach's α greater than 0.8 is commonly stated as a good value for internal consistency (Bortz & Döring, 1995). Reported main effects for lateral and frontal distances indicate an increased motion acceptance for greater maintained distances. Within lateral distance variations, no significant differences occur for 0.2m/0.3m, 0.3m/0.4m, and 0.4m/0.5m by computing Bonferroni post-hoc tests.

Within frontal distances, significant differences occur for 0.5m/0.95m, 0.5m/1.1m, 0.65m/0.8m, 0.65m/0.95m, 0.65m/1.1m, and 0.8m/1.1m. All other differences among the frontal mean scores are not significant.

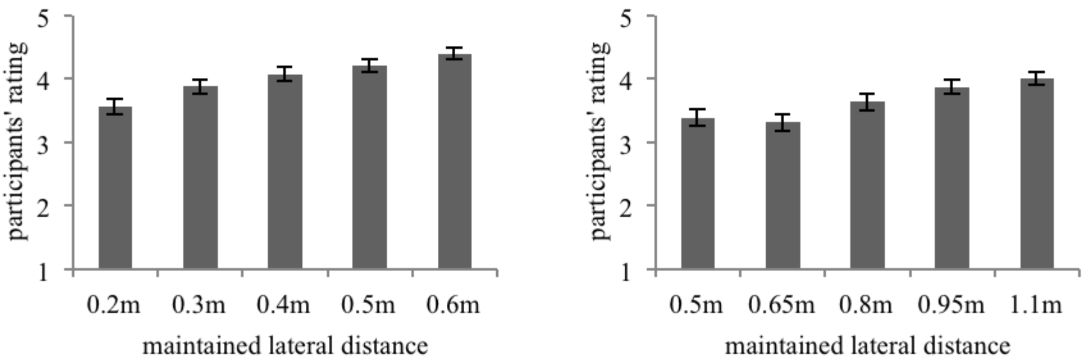

Figure 4-6 illustration of the motion acceptance for lateral and frontal distances
(Rating scale: 1 = strongly disagree, 5 = strongly agree)

In Figure 4-7 gained results regarding the expectation conformity towards the motion behavior of the mechanoid are illustrated. Charted results show that greater lateral and frontal distances rather meet participants' expectations except 1.1m within frontal distances. Bonferroni post-hoc comparisons show significant differences for 0.2m/0.4m, 0.2m/0.5m, 0.2m/0.6m, and 0.3m/0.6m. Remaining differences in the mean scores of lateral distances are not significant.

Within frontal distances, significant differences occur for 0.5m/0.8m, 0.5m/0.95m, 0.5m/1.1m, and 0.65m/0.95m.

The autonomous assistant's motion behavior was exactly like I expected it?

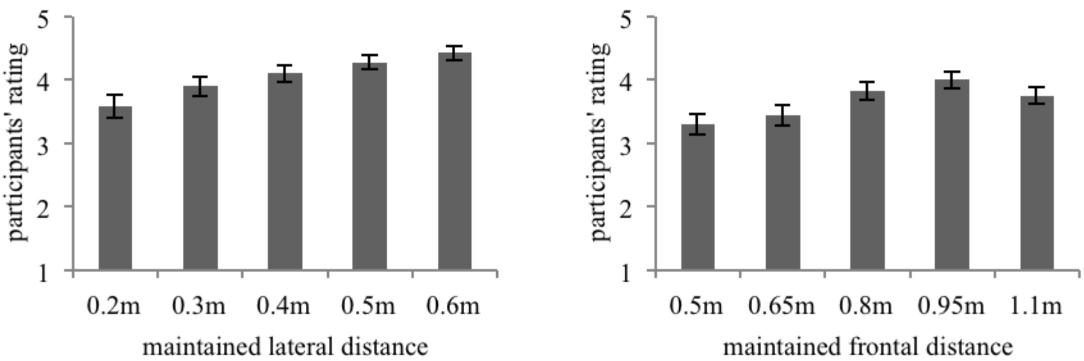

Figure 4-7 illustration of the expectation conformity for lateral and frontal distances
(Rating scale: 1 = strongly disagree, 5 = strongly agree)

Figure 4-8 shows the attained ratings of participants' perceived safety around the mechanoid. Overall, it is found that greater distances lead to increased feelings of safety compared to smaller distances. Within lateral distances, significant differences in the mean scores occur for 0.2m/0.4m, 0.2m/0.5m, 0.2m/0.6m, 0.3m/0.5m, 0.3m/0.6m, 0.4m/0.5m, 0.4m/0.6m.

Among frontal distances, significant differences are assessed for all means except 0.5m/0.65m, and 0.95m/1.1m.

How safe did you feel around the autonomous assistant?

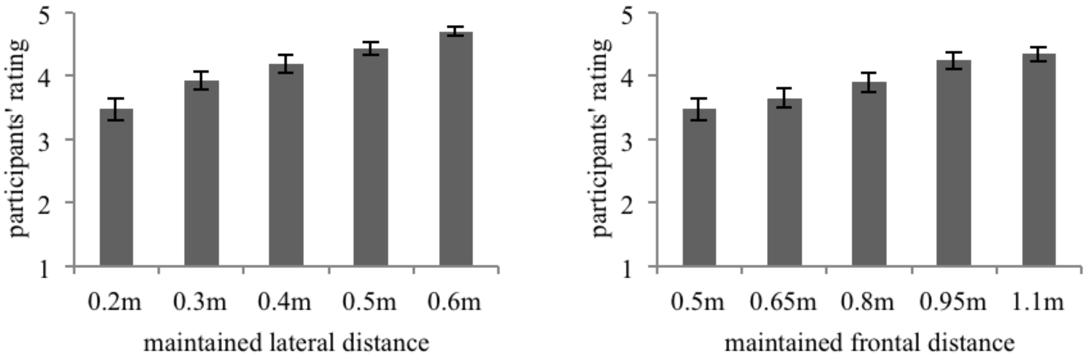

Figure 4-8 illustration of the perceived safety for lateral and frontal distances
(Rating scale: 1 = not at all, 5 = very)

The perceived human likeness is presented in Figure 4-9. As shown in the lateral distance chart, greater distances are perceived and rated as more human-like compared to smaller distances. In contrast, this is not observed for frontal distances. The approximate mean frontal threshold of comfort, which is empirically gained in the previous study, receives the highest rating. Maintained distances below and above receive a lower rating, respectively. However, these differences are not significant. With respect to lateral distance ratings, bonferroni post-hoc tests show significant differences for 0.2m/0.3m, 0.2/0.4m, 0.2m/0.5m, 0.2m/0.6m, and 0.3m/0.5m.

Within frontal distances, significant differences are obtained for 0.5m/0.8m, 0.65m/0.8m, and 0.65m/0.95m.

How human-like was the autonomous assistant's motion behavior?

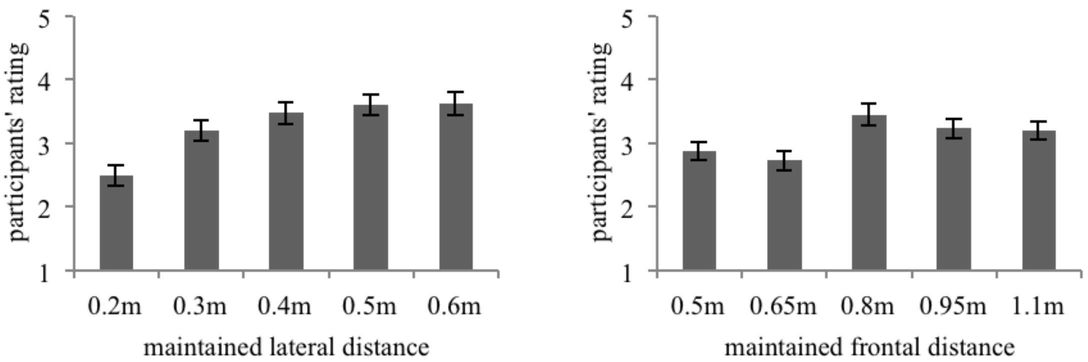

Figure 4-9 illustration of the perceived human likeness for lateral and frontal distances
(Rating scale: 1 = not at all, 5 = very)

Figure 4-10 depicts the perceived proximity of the mechanoid compared to a human in the same situation. Findings indicate that the empirically gained mean lateral (0.4m) and mean frontal (0.8m) distances from the first study are rated as most similar to a usual human distance behavior in the same situation. Smaller maintained distances are perceived as closer compared to a human and greater distances are perceived as farther compared to a human. Within lateral distances, significant differences occur between all means except 0.5m/0.6m.

Among frontal distance variations, significant differences occur for all means except 0.5m/0.65m, and 0.95m/1.1m.

Compared to a human in the same situation, the autonomous assistant approached me?

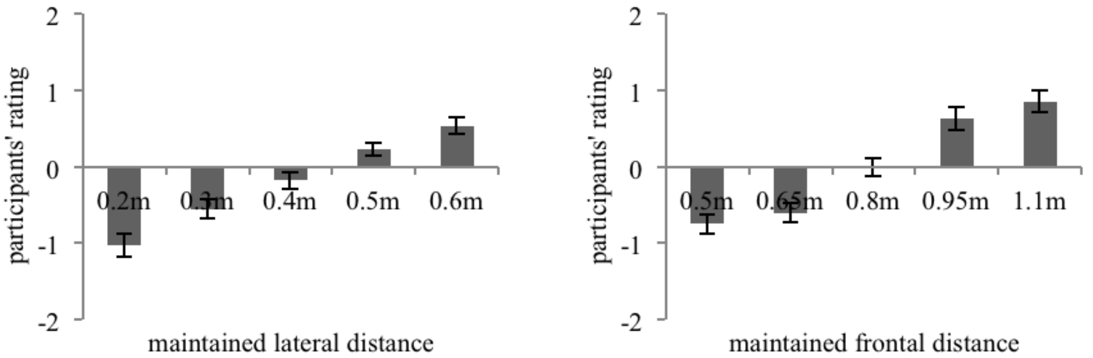

Figure 4-10 illustration of the perceived proximity compared to a human for lateral and frontal distances (Rating scale: -2 = way closer, 0 = similar to a human, 2 = way farther)

As a next step, multiple Pearson's correlations are run to determine the relationship between all dependent variables (Bortz & Döring, 1995). Therefore, one Pearson's correlation is computed for each frontal and lateral distance manipulation. For each significant relationship between two variables, Table 4-4 shows the corresponding r_{min} and r_{max}. (r_{min} = the smallest assessed r score for this relationship, r_{max} = the greated assessed r score for this relationship). In literature, the following conventions for r are presumed: no relationship (0.01 to 0.19), weak positive relationship (0.20 to 0.29), moderate positive relationship (0.30 to 0.39), strong positive relationship (0.40 to 0.69), and very strong positive relationship (> 0.70). The same negative ranges account for negative relationships (Bortz & Döring, 1995).

Relationship	$\mathbf{r_{min}}$	$\mathbf{r_{max}}$
motion acceptance & spatial discomfort	-0.39	-0.71
motion acceptance & perceived proximity	-0.32	-0.73
motion acceptance & expectation conformity	0.43	0.75
motion acceptance & perceived safety	0.50	0.78
motion acceptance & human likeness	0.36	0.66
expectation conformity & human likeness	0.23	0.50
perceived proximity & spatial discomfort	0.42	0.86
spatial discomfort & perceived safety	-0.43	-0.85

Table 4-4 Pearson's correlations for all dependent variables
Note: only correlations with a two-tailed significance on a significance level of $\alpha=0.05$ are reported

Lastly, potential influences of the captured control variables on each dependent variable are analyzed by computing 4 two-way MANOVAS with distance (frontal or lateral) serving as a within-subjects variable and one of the control variables serving as a between-subjects variable for each block. The MANOVAS do not show any significant impact. Thus, participants' sensations in terms of measured dependent variables are not significantly affected by participants' gender, professional background, prior experience with autonomous systems, or prior experience with the applied '*transport assistant*'.

4.3 Discussion

In retrospect, this follow-up study primarily aims to validate previously assessed mean distances (study I) in relation to an autonomously moving mechanoid (transport assistant) in a hallway. Furthermore, the study intends to explore the potential relevance of proxemic behavior on the overall motion acceptance of a social service robot. Therefore, diverse frontal approach and lateral passing distances are derived from the first study and are autonomously maintained by the same mechanoid in the same hallway-like setting. In order to assess participants' relevant sensations, questionnaires are applied.

To sum up, attained findings partly validate the previously gained spatial mean thresholds of comfort in the first study. Of particular interest to note is that the accepted frontal mean distance seems to increase due to the autonomously approaching robot (frontal mean distance study II: > 0.8m and < 0.95m, frontal mean distance study I: 0.77m). The same effect is not observed for the lateral passing scenario (lateral mean distance study I and II: ~0.4m). In regard to the third research question of this study, findings show that the proxemic behavior of an autonomous mechanoid (transport assistant) can, either positive or negative, significantly affect the perceived motion acceptance. Partly in line with formulated assumptions, some greater distances than the spatial mean thresholds cause higher ratings of motion acceptance, and some smaller distances lead to lower ratings. The presented findings suggest that the impact on motion acceptance seems to be limited to a minimal difference in distance. In particular, this study suggests that only frontal distance changes of at least 0.3m and only lateral distance changes of at least 0.2m provoke significant changes in the overall motion acceptance. In addition, results indicate that frontal distance changes of 0.15m and lateral distance changes of 0.1m do not significantly affect the motion acceptance yet.

Moreover, it is important to note that selected distance intervals lead to significant effects throughout all measured dependent variables. In addition, nearly all effect size calculations of the significant dependent variables show large effects, meaning that the total variance of the dependent variables is to an estimated large extent explained by the effect variance. Therefore, attained findings provide empirical evidence for a general relevance of proxemics in the examined scenario. This is discussed in greater detail in the following paragraphs.

With respect to the developed first hypothesis, analyzed proximity ratings of frontal distances show no significant support. The corresponding frequency of '*not too close at all*' ratings reveals that less than half of all participants (37,5%) accepted a distance approximately corresponding to the previously gained frontal mean threshold of comfort in the first study (~0.8m). In addition, attained post hoc comparisons reveal significant differences between the distance intervals (0.65m/0.8m, 0.8m/0.95m). However, according to the first hypothesis, approximately half of the subjects should accept 0.8m. Thus, the first hypothesis is rejected. However, in general this data highlights the importance for an autonomously approaching mechanoid to maintain a frontal threshold of comfort in a hallway. In regard to the frequency ratings, accepted frontal mean distances can be assumed to be greater than 0.8m and smaller than 0.95m. Furthermore, attained results show that the highest portion of participants (75%) did not feel intruded in their personal space at a distance of 1.1m. In contrast, only a very small minority of all participants (7,5%) accepted a distance of 0.5m.

In line with these proximity ratings, the perceived spatial discomfort is significantly higher for maintained frontal distances below 0.8m, and significantly lower for maintained distances above 0.8m. Thus, a subjectively perceived *too close* distance also evokes a significantly higher feeling of discomfort, and vice versa. This relationship is also significantly supported by retrieving strong to very strong positive correlations between these two variables. Therefore, as similarly postulated in HHP (e.g. Watson, 1970), this finding supports the relevance of personal space for avoiding feelings of discomfort when being approached by an autonomous mechanoid in a hallway. Furthermore, this finding aligns again to previous research in HRP (e.g. Koay et al., 2007; Brandl et al., 2013), suggesting the personal zone as the most suitable for acceptable frontal robot-to-human approach distances. Interestingly, the frontal mean distance seems to be greater toward the autonomously approaching mechanoid than the self-controlled approaching mechanoid. It can be assumed that a decreased locus-of-control in this experiment compared to the first study may cause this effect. However, according to Hayduk (1978), the *Duke-Nowicki Social Learning Theory* rather poses a minor variant of the *Dosey-Meysels Protection Theory.* Thus, it can be further assumed that a decreased control of the robot simultaneously evokes a higher level of threat to the subjects. Accordingly, their desired frontal minimum distance increases.

With respect to the second hypothesis, the assessed frequency of '*not too close at all*' ratings shows that approximately half of the participants (55%) do not perceive a distance that corresponds to the previously assessed lateral mean distance as *too close*. Thus, it can be assumed that participants' accepted lateral mean distance is around 0.4m in the present experiment. Accordingly, the second hypothesis is supported.

In addition, the data shows that the largest portion of '*not too close at all*' ratings (92,5%) occurrs when the mechanoid is autonomously passing at 0.6m. Contrarily, only a small minority of participants (15%) rates an autonomously passing mechanoid at 0.2m as '*not too close at all'*. Again, this data is supported by significant post-hoc comparisons between the accepted mean distance and distances below or beyond it. As for frontal distances, the present experiment supports the importance of maintaining lateral spatial thresholds of comfort in a scenario, incorporating an autonomous mechanoid. Particularly, this study poses a systematic exploration of an acceptable lateral passing behavior in a hallway. It further shows that, similar to frontal zones of personal space, lateral zones also contain spatial thresholds of comfort. Thus, attained findings support initial lateral distance explorations by Pacchierotti et al. (2006). However, designing an acceptable lateral proxemic behavior for an autonomously passing robot should be subject of investigation in future research.

In addition, findings suggest support for previous results from study I, revealing that acceptable lateral distances are smaller than frontal ones. As found in human-human proxemics (e.g. Ashton & Shaw, 1980) and as found in the first experiment of this dissertation, accepted frontal mean distances are approximately twice as big as lateral distances. However, as mentioned in the discussion of the first study, the pursued approach in the present study addresses lateral passing distances, which limits the comparability to previous HHP studies (e.g. Ashton & Shaw, 1980; Hayduk, 1981). Hence, this subject should be addressed in future studies.

In line with attained results for frontal distances, the perceived spatial discomfort corresponds to participants' ratings of the perceived proximity toward the passing mechanoid. Thus, subjects are also sensitive to lateral personal space invasions, which results in higher levels of perceived discomfort, and vice versa. These findings additionally support the relevance of exploring and designing an acceptable lateral passing behavior for an autonomously moving mechanoid in a hallway.

In regard to underlying psychological motives, it remains questionable at this point why a decreased level of locus of control does not influence participants' lateral distance preferences. Possibly, the overall perceived threat is significantly lower in lateral scenarios than in frontal ones due to a well-predictable passing maneuver. It can be assumed that subjects' perceived levels of threat are generally higher in frontal approach scenarios due to the potential danger of a collision, which does not exist during lateral scenarios. However, this subject should be further investigated. One future approach, for instance, could design an exploration of accepted lateral distances when a robot approaches participants from the side.

As an interim conclusion, it can be noted that the previously gained frontal and lateral mean thresholds of comfort are partly validated in the present experiment. Interestingly, the frontal mean threshold of comfort seems to increase due to the autonomously approaching robot, but this effect does not occur for the lateral passing distance. In general, the present experiment shows that participants' personal space (frontal and lateral zones) needs to be considered in order to avoid feelings of discomfort in the explored context. In regard to the first two research questions of this study, indications for accepted frontal (>0.8m, <0.95m) and lateral mean distances (~0.4m) are attained.

However, it is of particular importance to discuss the practical relevance of these mean thresholds of comfort. Gained findings suggest that a corresponding distance management of an autonomously approaching or passing mechanoid would exclusively avoid a personal space penetration in approximately 50% of this sort of encounter with a standing human in a hallway. Accordingly, in approximately 50% of all situations this proxemic behavior adjustment would still cause feelings of discomfort. Taken this into account, the examined distance range unveils the largest portion of comfortable participants at frontal distances of 1.1m and at lateral distances of 0.6m. Put simply, in order to prevent an autonomously driving robot from invading the personal space of a large majority of standing persons in a hallway (approach: 75%, passing: 92,5%), the data suggests that the robot should minimally maintain a frontal approach distance of 1.1m and a minimal lateral passing distance of 0.6m. In favor of high individual differences in distance preferences, as already suggested in HHP (Hayduk, 1978), these distances seem to be more appropriate for a societal integration. Moreover, these suggested values as well as assessed mean distances are greater than most previously gained distances (e.g. Pacchierotti et al., 2006; Walters et al., 2009; Takayama & Pantofaru, 2009; Kamide et al., 2014), which possibly occurs due to a higher spatial density and/or methodological differences. Increased interpersonal distances due to a higher spatial density have been already presumed in HHP research (Dabbs et al., 1973; Hayduk, 1983; Evans & Werner, 2007), and thus, the present work poses support for a similar effect in HRP.

Furthermore, as already noted in the discussion of study I, it can be assumed that a less bulky, less cubic-like outward robot design (e.g. PeopleBot compared to transport assistant) might generally decrease people's accepted robot-to-human frontal approach distances. However, the most comparable study (Brandl et al., 2013), regarding methodological details, has shown very similar frontal approach distances of approximately 1.2m at a slightly faster velocity of 0.75m/s. In this study, the employed care-o-bot, however, neither is a very slim robot and it is also considerably taller than the transport assistant, which potentially evokes greater distance preferences. Though the effects of robot height on HRP remain inconclusive to date, evidence for this assumption has been shown in HHP (e.g. Caplan & Goldman, 1981). Future studies should further investigate the interplay of outward robot design and distance preferences. In particular, a potential effect on lateral passing distances is highly unexplored to date.

With respect to the third hypotheses, computed means of motion acceptance ratings and subsequent Bonferroni post-hoc tests are analyzed. At a first glance, autonomously maintained frontal and lateral distances below the previously assessed mean distances cause lower ratings of motion acceptance, and vice versa. However, post-hoc comparisons exclusively reveal significant differences between the previously gained thresholds (frontal: 0.8m, lateral: 0.4m) and some smaller maintained distances (frontal: 0.65m, lateral: 0.2m) as well as some greater maintained distances (frontal: 1.1m, lateral: 0.6m). Consequently, only partial support for the third hypothesis is found.

The attained data reveals that not all factor levels of the examined distances lead to a significant alteration in the overall motion acceptance ratings. In particular, the least and greatest maintained distances of the tested distance range (except minimal frontal distance: 0.5m) evoke significant changes in the motion acceptance. As a possible explanation, it can be assumed that relatively small distance changes of 0.1m (lateral) or 0.15m (frontal) do not affect the overall perceived motion acceptance. However, greater distance changes of 0.2m (lateral) or 0.3m (frontal) already significantly influence it. Thus, attained findings partly support the assumption that proxemic behavior of an autonomously moving robot influences the overall motion acceptance. However, based on the obtained data the level of relevance of this influence cannot be completely determined. Potential influences of other motion attributes, such as acceleration or speed, were not examined in this study. Thus, this subject should be investigated in future studies by additionally manipulating other robotic motion features. Particularly, a potential influence of robot speed should be addressed in future examinations since its significant impact on people's distance preferences has been shown by various previous research, including the first study of this dissertation (see section 3).

Nonetheless, the relevance of an acceptable proxemic behavior for the overall motion acceptance in the examined context is supported. This is additionally corroborated by assessing moderately negative to very strong negative correlations between motion acceptance and the perceived proximity as well as the perceived spatial discomfort. In line with these correlations, frontal (1.1m) and lateral (0.6m) distances, which were not *too close* for most participants and evoked the least level of discomfort also received the highest motion acceptance rating.

Thus, in regard to the last research question of this study, it can be concluded that the examined distance behavior of an autonomously moving robot partly affects the overall motion acceptance. Precisely, increasing lateral distance changes of around 0.2m and increasing frontal distance changes of around 0.3m than the assessed mean distances cause a significantly higher motion acceptance. Moreover, decreasing lateral distance changes of around 0.2m and decreasing frontal distance changes of around 0.3m than the assessed mean distances cause a significantly lower motion acceptance. However, the examined distance ranges do not permit robust interpretations whether smaller distance changes, for instance 0.15m (lateral) or 0.2m (frontal), would already significantly affect the motion acceptance. This needs to be investigated in future studies. This finding also poses a support for the general concept of the left hand side of the Uncanny Valley (Mori, 1970). By altering a single motion property of the robot, the motion acceptance increased or decreased. However, as already stated in section 2.6, social human behavior cannot be carelessly copied to robots. This study reveals that underlying social conventions of human motion behavior (proxemics) are also relevant in HRI, and it shows that substantial psychological motives can be carried over to HRP. However, that does not necessarily mean to copy usual interpersonal distances between humans to robots.

As a relevant practical implication, the following can be suggested: Roboticists should at least ensure to design a proxemic behavior for an autonomously moving robot in a hallway that would not overshoot the lateral mean distance by more than 0.1m, and the frontal mean distance by more than 0.15m. Instead, robotic engineers should increase lateral mean distances by more than 0.1m, and frontal mean distances by more than 0.15m for improving the overall motion acceptance of the robot. Thus, it can be further assumed that a slightly sub-optimal distance behavior of a robot does not immediately lead to an decreased motion acceptance. This can be advantageous for potential real-world applications whose sensors or software cannot guarantee a very accurate distance behavior, or for saving performance capacities in favor of other, perhaps more critical robot capabilities. However, up to this point, these conclusions are only valid for the examined research context.

Altogether, the present study suggests to maintain greater lateral passing (0.6m) and frontal (1.1m) approach distances than the gained mean thresholds of comfort in the first study in order to avoid feelings of discomfort for a large majority of individuals, and in turn positively affect the overall motion acceptance of an autonomously driving robot in a hallway. An increased motion acceptance is generally based on more positive feelings towards a robot, such as a higher predictability and trust for future movements and thus, contributes to a more effective indirect interaction, which is a substantial component of accepted robot integration into human environments.

4.4 Conclusion

To conclude, the study poses a first systematic evaluation of accepted frontal and lateral distances for an autonomously approaching and passing mechanoid in a hallway. However, the accepted mean distances lack a high practical relevance in favor of large individual differences in personal space. In order to avoid spatial discomfort for a large majority of standing individuals, the distance ranges and corresponding findings suggest that frontal approach distances of 1.1m and lateral passing distances of 0.6m are more appropriate. In particular, obtained data shows that 75% of the sample perceives no frontal personal space violation, and 92,5% no lateral personal space violation when these distances are maintained. Thus, findings suggest that roboticists should rather refer to these values than the assessed mean scores when implementing acceptable proxemics robot behavior into future software frameworks for an autonomously moving robot in a hallway. Whether greater distances would increase these percentages can only be assumed and should be subject of further investigations. In addition, the present experiment exclusively reveals insights into an acceptable distance calibration for a first contact scenario. Since previous research has shown significant habituation effects on people's distance preferences (e.g. Koay et al., 2007; Walters et al., 2011), future investigations should shed light on the validity of these distances over time.

Moreover, gained motion acceptance findings can be beneficial for future market-ready systems, which lack a high proxemic accuracy for various reasons. However, up to this point, the proxemic behavior's precise level of relevance for an acceptable motion behavior remains open. Further motion attributes of a robot and their possible interplay with proxemics, and potentially other effects on motion acceptance should be researched in the future. Lastly, these conclusions are only valid within the confines of the examined research context.

5 Study III: Exploration of Accepted Distances Toward Another Autonomously Approaching and Passing Mechanoid (Beam) in a Hallway

The next empirical step of this dissertation primarily aims to validate the attained distance findings from study II in relation to another autonomously moving mechanoid (Beam) in a hallway. In order to permit comparable results, it is essential to align the design of this study as similar as possible to study II.

A second research goal of this experiment involves the exploration of a robot's level of human likeness on accepted frontal approach and lateral passing distances in a hallway. In addition, this study aims to further explore the relevance of a robot's proxemic behavior on the overall motion acceptance.

In sum, the following central research questions are answered by the present study:

1. Which frontal distance does a standing person accept from another autonomously approaching mechanoid (Beam) in a hallway?
2. Which lateral distance does a standing person accept from another autonomously passing mechanoid (Beam) in a hallway?
3. Does the distance behavior of an autonomously moving mechanoid (Beam) affect the motion acceptance of this robot?
4. Are subjects' distance preferences influenced by Beam's level of human likeness?

As expounded in the theoretical foundation, a central problem in past HRI research has been posed by a high variance of applied robotic systems. This problem has also been found amid more specific HRP studies (see section 2.7.3.1). Variously employed robotic research platforms have differed in numerous characteristics, such as human likeness, height, size or technical motion specifications (e.g. speed). Thus, existing findings are difficult to relate to each other and therefore complicate a deduction of generic results. Accordingly, this study aims to validate previously attained findings in relation to another autonomously moving mechanoid (Beam).

Regardless of the applied robot type, all reviewed HRP studies have revealed a general relevance for maintaining spatial thresholds of comfort. Accordingly, it is hypothesized in the present experiment that the previously attained accepted mean distances (see study II, section 4) also apply to another autonomously approaching or passing mechanoid (Beam) in a hallway.

In addition, as elucidated in the theoretical part of this work, the outward design regarding a robot's human likeness, has posed a very prominent debate in the HRI community (e.g. Hinds et al., 2004). According to the stated suggestions of the left-hand side of the Uncanny Valley (Mori, 1970), a more human-like robot design leads to a higher level of familiarity, i.e. to generally improved attitudes towards the robot (Bartneck et al., 2009b). Therefore, it is assumed that a humanized appearance of Beam will cause higher ratings of human likeness/likeability/animacy/familiarity than the original, machine-like appearance of Beam.

However, as shown in reviewed HRP studies, a potential influence of a robot's level of human likeness on people's distance preferences has rarely been investigated yet. Initial findings have indicated increased frontal distance preferences for more human-like looking robots (Butler & Agah, 2001; Koay et al., 2007). Thus, the present experiment hypothesizes that a more human-like looking Beam leads to increased frontal distance preferences. Based on this assumption, a similar effect is predicted for lateral distance preferences.

Therefore, the following five hypotheses are formulated for the present study:

Hypothesis I: *The accepted frontal mean distance toward an autonomously approaching Beam in a hallway corresponds to the accepted frontal mean distance in the second study (>0.8m, <0.95m).*

Hypothesis II: *The accepted lateral mean distance toward an autonomously passing Beam in a hallway corresponds to the accepted lateral mean distance in the second study (~0.4m).*

Hypothesis III: *Maintained distances that correspond to the accepted mean distances in study II positively affect the overall motion acceptance of an autonomous Beam in a hallway opposed to smaller distances. In addition, maintained distances that surpass the accepted mean distances in study II lead to higher ratings of the overall motion acceptance.*

Hypothesis IV: *A humanized appearance of Beam causes higher ratings of human likeness/likeability/animacy/familiarity than the original appearance of Beam.*

Hypothesis V: *A more human-like looking Beam leads to increased accepted frontal approach and lateral passing mean distances opposed to a machine-like looking Beam, which is autonomously moving in the same scenario.*

5.1 Method

As already stated in the introduction of this comparative study, it was essential to align as much study details as possible to the previously conducted experiment. A precise description of the conceptualized methodology is given in the following sub-sections.

5.1.1 Participants

Among the 40 participating subjects were 22 (55%) females and 18 (45%) males with an average age of 35.2 years (SD = 11.7). The sample consisted of 23 US Americans (57.5%), followed by 13 Germans (32.5%), 2 Russians (5%), 1 Slovenian (2.5%) and 1 Swiss (2.5%). Nearly half of the participants had a non-technical professional background (47.5%) as opposed to 21 subjects with a rather technical background (52.5%). The majority of the subjects (90%) did not at all or only rarely exercise professional or leisure activities with any kind of robotic systems. Approximately half of the subjects were internally recruited and this led to some familiarity with Beam (40%). However, most of the participants had only seen Beam roaming around, but had not encountered it in a hallway. None of the subjects had known the examiner's confederate, who secretly operated Beam, before. All participants received a $20 monetary compensation for their participation.

Basic sample characteristics were comparable to study II (adults around 30 years, similar gender distribution, similar professional background, similar prior experience with robots). As for study I and II, unpaired t-tests were computed and the findings are reported in Appendix C. According to Hall (1966) and Nanda and Warms (2010), people from North America and Northern Europe both can be classified as non-contact cultures. Thus, the underlying spatial conventions of all participants were assumed to be comparable.

5.1.2 Material

In contrast to the first two studies of this dissertation, the present experiment took place in the robotics lab of the Robert Bosch Research and Technology Center in Palo Alto, USA. Independently of another location, the lab permitted an identical preparation of the previously applied hallway-like setting. In particular, the hallway also included walls with white film, a door-like entrance, and the same dimensions (6m long, 2.90m wide). Additionally, blue markings on the ground were identically installed as described in the first and second study of this dissertation (see section 3.1.2 and 4.1.2). Thus, starting positions of Beam and participants comprised the same distances to each other. Moreover, as in the second study, a small round table, which served the participants to complete the questionnaires, was placed in the rear left corner of the hallway (from Beam's point of view). The experimental setting is shown in Figure 5-1 and 5-2.

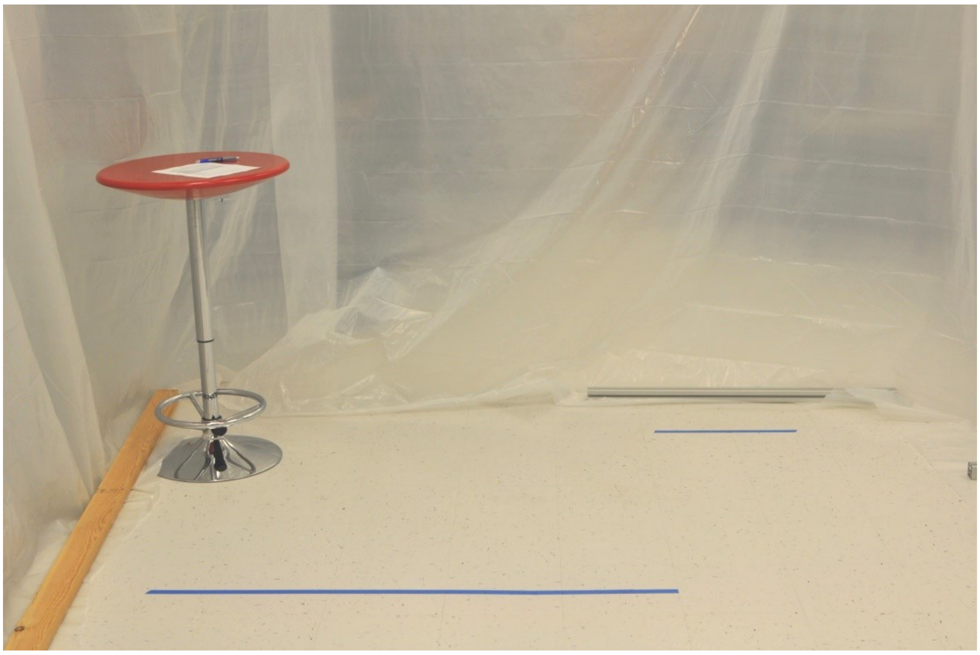

Figure 5-1 experimental setting from Beam's point of view

Figure 5-2 experimental setting from the participant's point of view

Beam's speed and acceleration values were identical to the used ones in the second study (see section 4.1.2). Thus, Beam moved at a speed of 0.6m/s and started/stopped with an acceleration of $2m/s^2$, $-2m/s^2$ throughout all experimental trials. For a more detailed description of Beam see section 1.4

With respect to the human likeness manipulation of Beam, its screen was either showing nothing (black) or a real human face. For the human-like version, a real face of a new Bosch employee was streamed live on Beam's screen in order to make Beam look more human-like. This new employee also served as the examiner's confederate, secretly operating the Beam throughout the whole experiment, which is explained in greater detail in sub-section 5.1.6. For the machine-like version, Beam's screen was covered with a thick black paper to make it look like a switched off monitor. It was impossible to switch off the screen while Beam was remotely operated by the confederate. Therefore, the black paper was applied. The used paper exactly covered Beam's screen and it was impossible to see the screen through it. Moreover, the black paper did not cover any of Beam's cameras. Both versions, machine- and human-like, of Beam are illustrated in Figure 5-3.

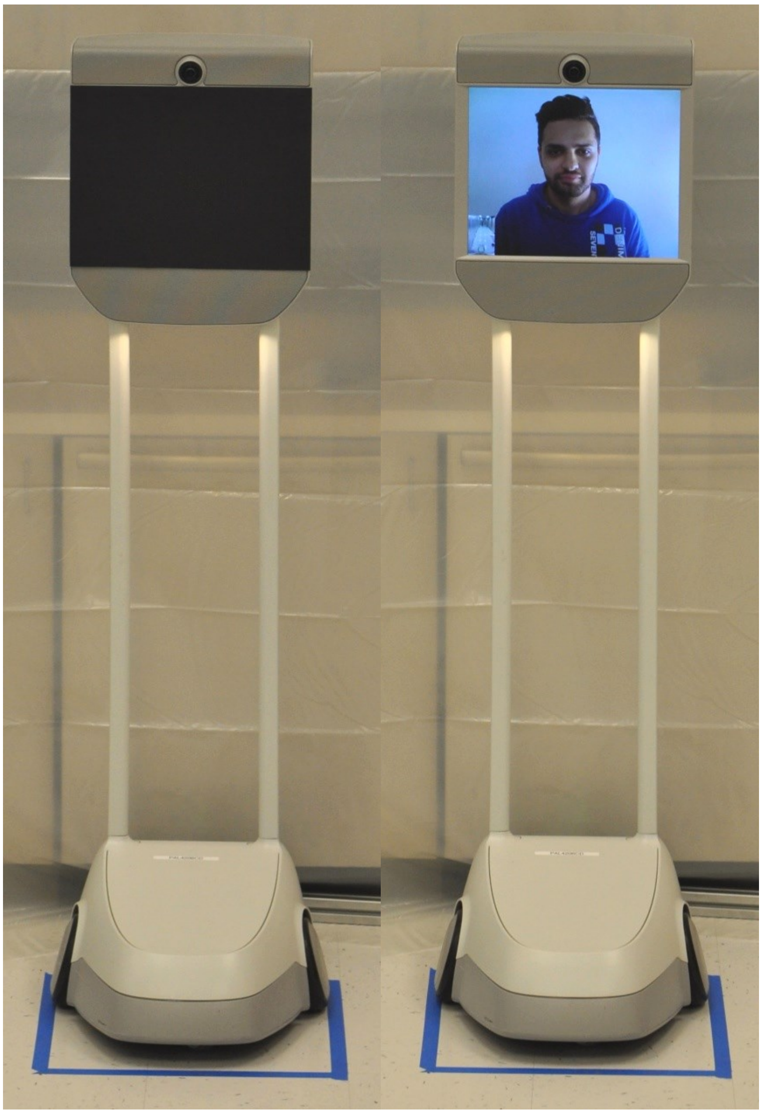

Figure 5-3 machine-like version of Beam (left) and human-like version of Beam (right)

5.1.3 Task

The entire experiment comprised two different tasks: Before entering the hallway and starting the proxemic investigation, participants were instructed to complete a set of questionnaires, assessing multiple feelings towards a presented robot in a picture. It was highlighted by the examiner that subjects should spontaneously rate the pictures, according to their individual impressions.

The second task involved entering the hallway and experiencing the variously maintained distances of Beam. As in the second study, subjects were not in control of the robot and were instructed to exclusively observe the autonomously approaching or passing Beam without changing their own starting position. Subsequently, they were asked to complete the same questionnaires as applied in study II. Again, it was highlighted that they should spontaneously indicate their sensations, and that neither false nor correct answers existed. The complete instruction sheet can be found in Appendix F.

5.1.4 Experimental Design

Altogether, the entire study involved two experimental designs: One for assessing the perceived human-likeness, likeability, animacy, familiarity and uncanniness of all employed robotic systems in this dissertation, and a second one for examining the central research questions on proxemics of this study.

The first design comprised two experimental blocks with a picture of the '*transport assistant*' serving as a first independent variable, and a picture of Beam (machine-like/human-like) serving as a second independent variable. Thus, in the first block, a picture of the previously employed '*transport assistant*' (same picture as shown in 1.4) and a picture of the machine-like version of Beam were rated by 20 participants. In the second block, the other half of participants rated a picture of the '*transport assistant*' and a picture of the human-like version of Beam. In both blocks, the order of presentation was completely balanced.

In regard to participants' ratings, the perceived human likeness, likeability, animacy, familiarity and uncanniness were assessed as dependent variables.

In order to examine the central research questions of this study, the second experimental design involved two experimental blocks as well. The first block comprised a 5 by 2 mixed design with frontal distance (0.5m/0.65m/0.8m/0.95m/1.1m) serving as a within-subjects factor and Beam's level of human-likeness (machine-like/human-like) as a between-subjects factor. The second block also comprised a 5 by 2 mixed design with lateral distance (0.2m/0.3m/0.4m/0.5m/0.6m) serving as a within-subjects factor and Beam's level of human-likeness (machine-like/human-like) serving as a between-subjects factor. 20 participants were randomly assigned to each block. As in the second study, the resulting 10 experimental trials for each factor of Beam's level of human likeness were completely randomized in order. Similar to the previous study, this design aimed to take already proven habituation effects into account.

Again, as in the second study, identical dependent variables were assessed (perceived proximity of Beam, perceived spatial discomfort, perceived motion acceptance, expectation conformity of the Beam's motion behavior, perceived safety around Beam, perceived human likeness of the Beam's motion behavior, and the perceived proximity of Beam compared to a human.)

5.1.5 Applied Questionnaires

In regard to the picture rating, the stated dependent variables human likeness, likability and animacy were assessed by applying the elaborated questionnaires from Bartneck et al. (2009b) (GODSPEED I, II, III – see Appendix A). Further dependent variables (familiarity, uncanniness) were captured by one item, respectively. Both items comprised a 5-point Likert scale (cf. Likert, 1932) ranging from 1 = strongly disagree, 2 = slightly disagree, 3 = neutral, 4 = slightly agree, to 5 = strongly agree. Altogether, three questionnaires, each one containing a picture of one robot appearance (transport assistant, machine-like Beam, human-like Beam), were conceptualized and are shown in Appendix G.

For assessing participants' feelings towards to the diversely maintained distances, the same questionnaires as in the second study were applied. The original versions were translated to English and reviewed by two English native speakers for comprehensibility. In addition, pre-tests were conducted to ensure that the translated versions are understandable. Both English versions of the original questionnaires are provided in Appendix H.

5.1.6 Autonomous Distance Regulation Technique

In line with the second study, a central goal of this experiment was to systematically evaluate an acceptable proxemic behavior of an autonomously moving robot and thus, participants were not in control of neither the machine-like nor human-like version of Beam. Furthermore, in order to explore a potential validity of previously attained findings (study II) for the present context, the identical distance ranges had to be autonomously maintained by Beam. Since Beam cannot autonomously drive, this sort of behavior had to be simulated again. In contrast to study II, another autonomous distance regulation approach was developed and employed.

As already introduced in section 2.7.3.5, a commonly applied experimental method in HRP research was also utilized in the present experiment: The Wizard-of-Oz approach (Dahlbäck et al., 1993; cf. Walters, 2008). This method was selected due to manifold reasons: First, Beam already had a completely elaborated functionality and interface for being remotely controlled. Second, Beam already is a commercially available product which complicates a potential software manipulation, such as recording specific trajectories and playback them. Thus, the WoZ approach saved a considerable amount of time and effort to accurately realize the different distance behaviors. Third, Beam cannot autonomously move and localize itself.

The examiner's confederate was disguised in a separate room before the subjects arrived to ensure that none of them had seen him before the experiment. He stayed in that room throughout the entire experiment, remotely controlling either the machine- or human-like version of Beam. For all human-like Beam trials, several details had to be consistent to ensure an identical face projection on Beam's screen. Therefore, his seating position, height of chair, camera settings, distance to the camera and visible parts of his clothes were consistently applied. In Figure 5-4, the disguised confederate's setting is shown.

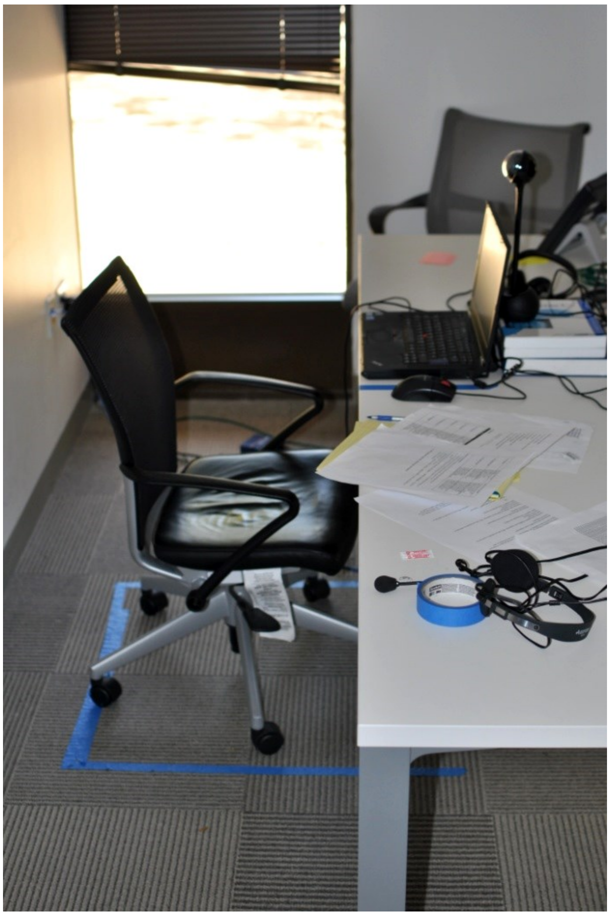

Figure 5-4 disguised setting of the examiner's confederate

The confederate remotely operated Beam by using the computer's keyboard. Importantly, the projection on Beam's screen made it impossible for participants to see any hand movements of the confederate. In addition, the confederate was muted during all experimental trials. In the human-like scenario, participants could visually interact with the confederate, and vice versa. In fact, subjects saw a real face incorporating blinking eyes. Thus, the confederate established eye contact with all subjects he frontally approached within human-like Beam trials. In contrast, this was impossible during machine-like scenarios. However, the black paper covering Beam's screen did not limit the confederate's control interface. Thus, throughout all experimental trials, the confederate could accurately maintain the necessary trajectories and frontal distances. By using Beam's down facing camera, the confederate had an unbiased perspective of its exact position (see Figure 5-5). Nonetheless, an intensive practice session before the experiment was conducted to ensure a distance management of Beam that was as consistent and accurate as possible.

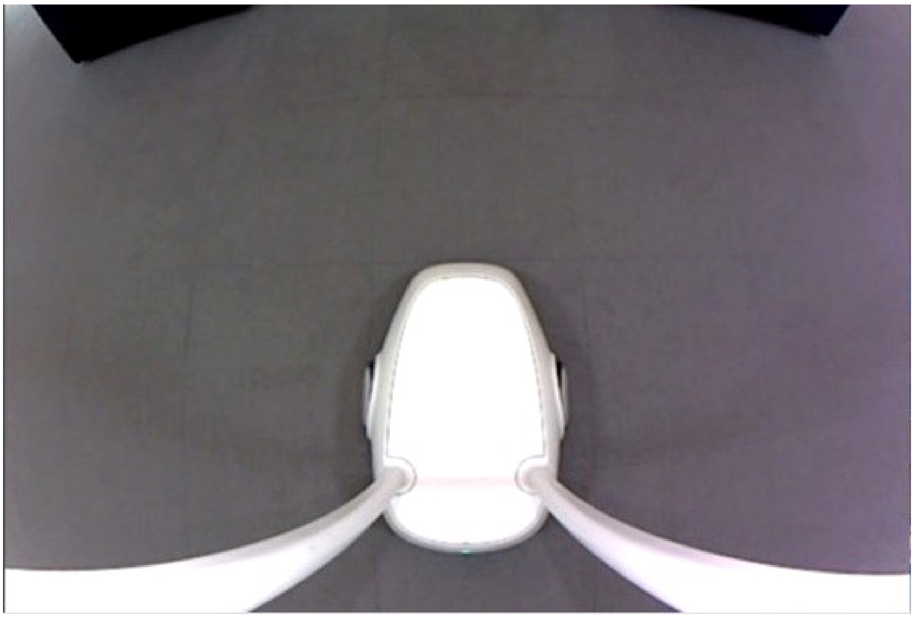

Figure 5-5 perspective of Beam’s down facing camera

In regard to the applied floor markings, the same method, as described in study II, was used for all lateral distance trials (nearly invisible grey markings). To ensure a consistent forward trajectory of Beam, its starting position was precisely marked as the one of the ‘*transport assistant*’ in the second study. The marked lateral distances were measured from Beam’s wheels since they were the closest body part of Beam when passing by participants. As in the second study, these distances had been accurately assessed before the experiment by placing Beam right next to the lateral starting position of participants. Furthermore, again as in the second study, participants’ lateral and frontal positions were identically adjusted, according to their biometrics (see section 4.1.6) and they were also instructed to hold these position during all trials. In contrast to the second study, the frontal distance regulation was also based on barely visible floor markings. These markings had been prepared before the experiment and were measured from the participants’ marked starting position to Beam’s most frontally outreaching part of its driving platform (see Figure 5-5). Since the confederate knew about the markings and intensively practiced the entire procedure, he mastered to maintain the frontal distances without any difficulty. In sum, upon practicing, this method led to a similar estimated level of accuracy than in the second study (0.05), which was assessed during pre-tests.

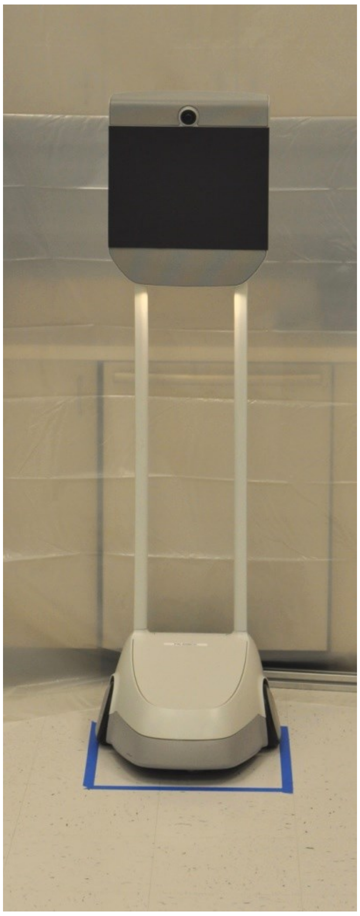

Figure 5-6 marked starting position of Beam

Lastly, to authentically simulate the autonomy of Beam, participants' were told that Beam is operated by the examiner via a simplified voice control. During the entire experiment Beam's microphones were activated that enabled the confederate to hear the examiner's commands. A set of seven commands had been developed and practiced before the experiment: *Let's go frontal 1, Let's go frontal 2, Let's go frontal 3, Let's go frontal 4, Let's go frontal 5, Let's go, Return,* and *Repeat.* Each *let's go frontal x* command was linked to the chronological order of frontal trials within the complete order of the randomized sequence of trials. The *let's go* command triggered each lateral trial, the *return* command made the confederate return Beam to its starting position, and the *repeat* command was used to repeat a trial in case something went wrong (e.g. inaccurate distance). This only happened four times during the entire experiment. None of the subjects seemed to be skeptical about the voice control. Instead, they were rather fascinated and impressed by the apparently well-performing voice control of Beam.

5.1.7 Procedure

Similar to the first and second study of this dissertation, the present experiment started off by introducing the participants to the scope of the study. Given a potential negative association with the term '*robot*' (Meyer, 2011), Beam was introduced as an autonomous, innovative telepresence system whose distance behavior is evaluated for research purposes of this dissertation. However, up to this point, participants had not seen Beam yet. Subsequently, subjects had to sign a consent form and received a preliminary questionnaire capturing the stated control variables of the sample (see Appendix J). At no point of the study, participants were informed about the possible remote control of robotic telepresence systems.

In the proximate step, the first part of the experiment, the picture rating, began. Subjects either received the questionnaire showing the '*transport assistant*' or one of the Beam versions first. Upon completing the two questionnaires, participants additionally received a written instruction which briefly explained the purpose and functionality of autonomous telepresence systems again and explicated the previously presented second task and upcoming procedure. As in study II, subjects were informed about a possible intervention by the examiner in the autonomous behavior of Beam at any time.

As soon as the participants entered the hallway-like setting, they saw Beam for the first time. Beam was already placed on its starting position and participants could ask final questions. Furthermore, the examiner notified all participants about the voice control of Beam. In the machine-like scenarios, participants were informed that Beam's screen was switched off and no user is currently telepresent. It was highlighted again that the robot will autonomously operate upon receiving the examiner's voice commands. In the human-like Beam scenarios, the examiner introduced the subjects to his confederate who could only wave back since he was muted. Again, it was highlighted that Beam will autonomously move and that this user was exclusively telepresent. Upon adjusting the first starting position of the participants, the examiner started the first experimental trial via voice command. In sum, subjects were exposed to 10 diverse trials followed by 10 questionnaires. The entire experimental procedure lasted for approximately one hour.

Upon the entire experiment, participants were completely debriefed about the simulated voice control, simulated autonomy and the faked black screen of Beam.

Importantly, none of them had noticed or been any skeptical about it. Figure 5-7, 5-8 and 5-9 show screenshots from a frontal and lateral trial.

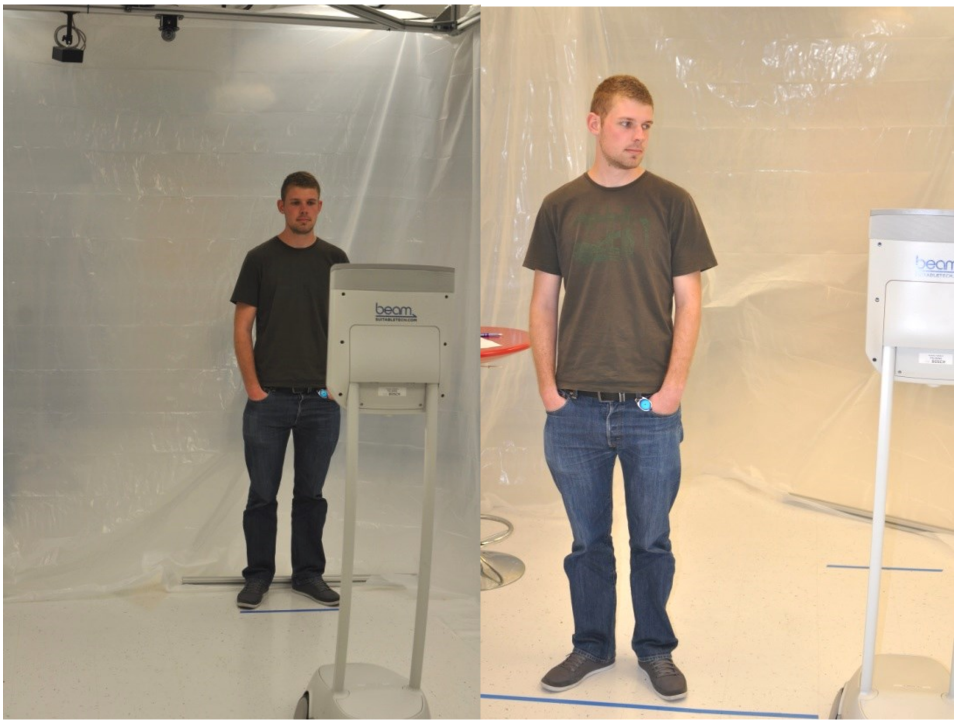

Figure 5-7 left: frontal trial, right: lateral trial

Figure 5-8 frontal trial with the machine-like version of Beam

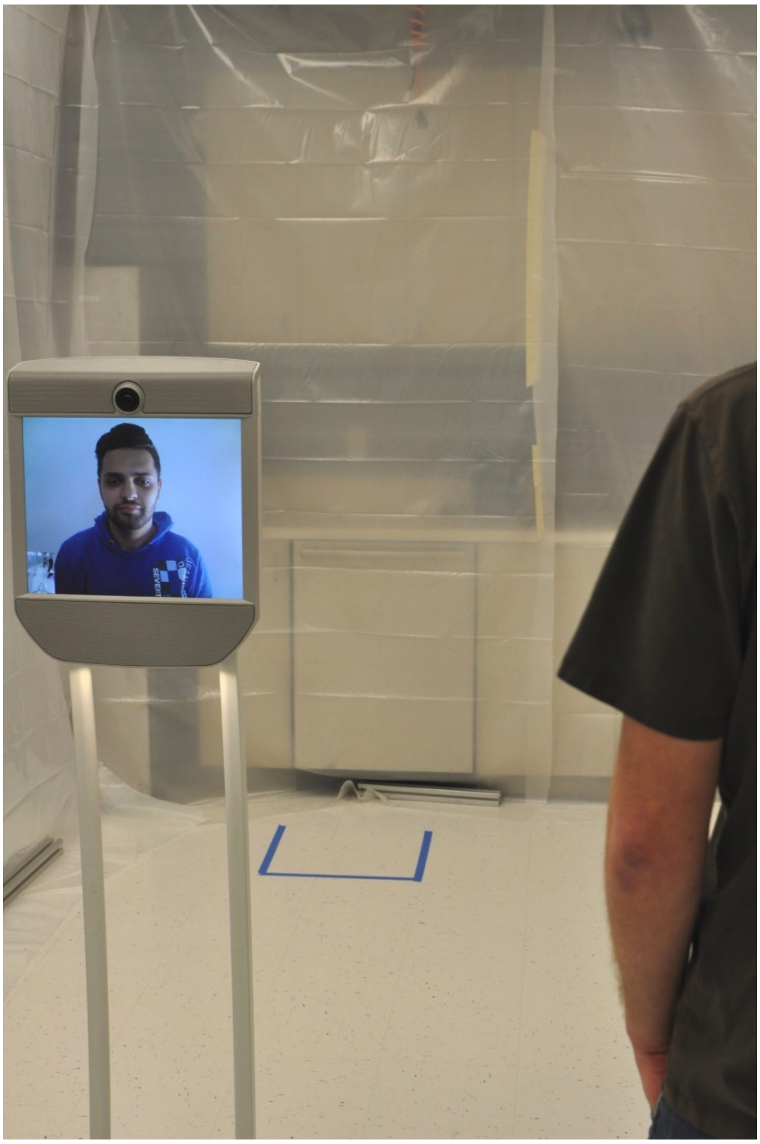

Figure 5-9 lateral trial with the human-like version of Beam

5.2 Results

5.2.1 Picture Rating

In order to assess differences between the robots, paired and unpaired t-tests are computed (Bortz & Döring, 1995). For assessing differences within one experimental block (transport assistant and one version of Beam), paired t-tests are computed. For assessing differences between the experimental blocks (machine-like Beam compared to human-like Beam), unpaired t-tests are computed. All required preconditions to apply this statistical analysis are fulfilled (cf. Rasch et al., 2010). By adjusting the significance level from α=0.05 to α=0.01, the multiple testing problem (cf. Bortz & Döring, 1995) is taken into account.

With respect to the first experimental block (transport assistant and machine-like Beam), all obtained means and their corresponding standard errors are charted in Figure 5-10. In addition, Table 5-1 shows the corresponding t and p values of all pairs in this block.

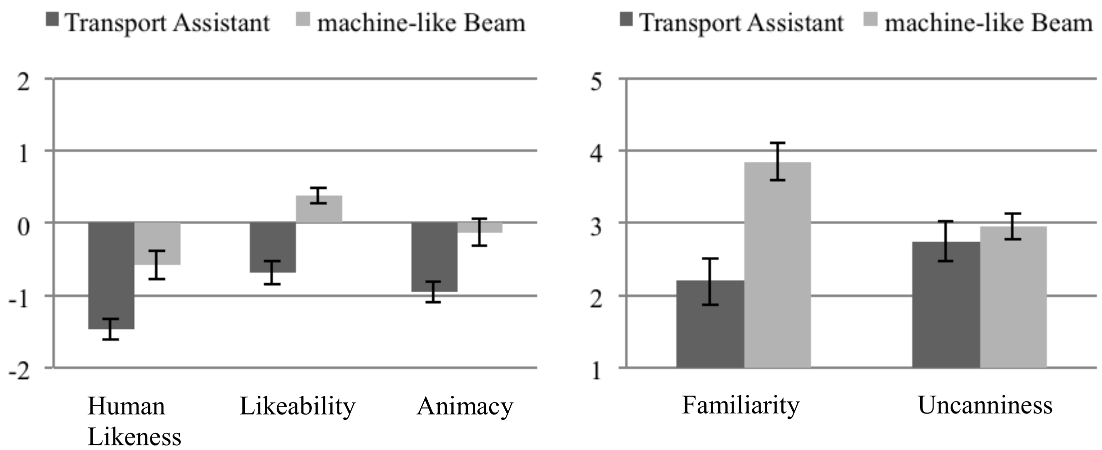

Figure 5-10 means and standard errors of the first block

Dependent variable (DV)	Type of Robot (IV)	t(19)	p
Human-Likeness	Transport Assistant	-3.887	0.001
	machine-like Beam		
Likeability	Transport Assistant	-5.447	0.000
	machine-like Beam		

Animacy	Transport Assistant machine-like Beam	-4.010	0.001
Familiarity	Transport Assistant machine-like Beam	-4.067	0.001
Uncanniness	Transport Assistant machine-like Beam	-0.677	0.507

Table 5-1 t and p values of all pairs in the first block

With respect to the second experimental block (transport assistant and human-like Beam), all gained means and corresponding standard errors are charted in Figure 5-11. In addition, Table 5-2 shows the corresponding t and p values of all pairs in this block.

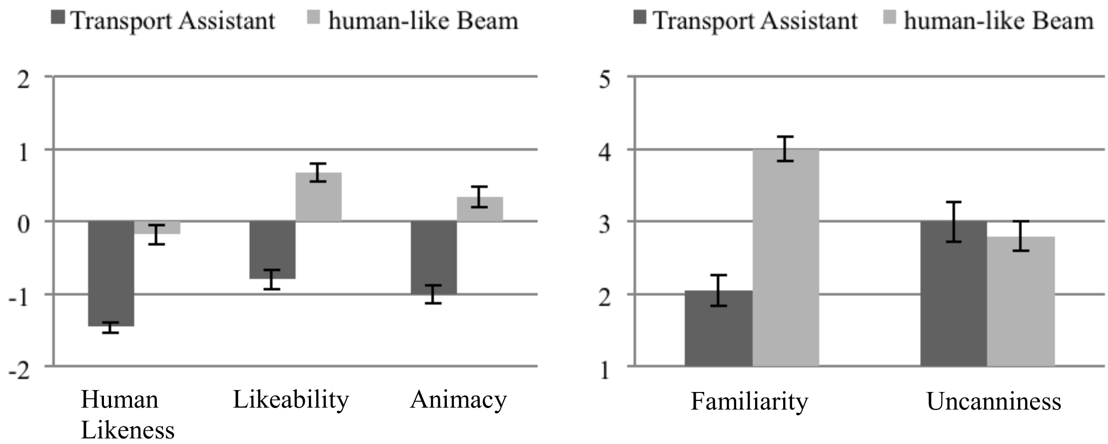

Figure 5-11 means and standard errors of the second block

Dependent variable (DV)	Type of Robot (IV)	t(19)	p
Human-Likeness	Transport Assistant human-like Beam	-8.807	0.000
Likeability	Transport Assistant human-like Beam	-8.585	0.000
Animacy	Transport Assistant human-like Beam	-6.722	0.000
Familiarity	Transport Assistant human-like Beam	-6.091	0.000
Uncanniness	Transport Assistant human-like Beam	-0.607	0.551

Table 5-2 t and p values of all pairs in the second block

With respect to a comparison of attained ratings for the machine- and human-like version of Beam, all obtained means and corresponding standard errors are charted in Figure 5-12. In addition, Table 5-3 shows the corresponding t and p values of all captured dependent variables.

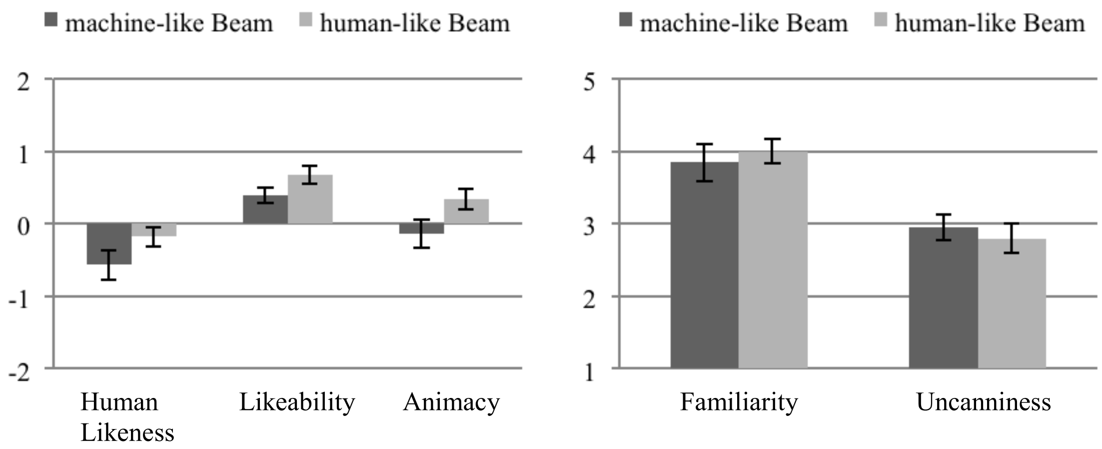

Figure 5-12 means and standard errors between the two blocks

Dependent variable (DV)	Type of Robot (IV)	t(38)	p
Human-Likeness	machine-like Beam human-like Beam	1.602	0.118
Likeability	machine-like Beam human-like Beam	1.661	0.105
Animacy	machine-like Beam human-like Beam	1.989	0.050
Familiarity	machine-like Beam human-like Beam	0.471	0.640
Uncanniness	machine-like Beam human-like Beam	-0.551	0.585

Table 5-3 t and p values of all machine- and human-like Beam comparisons

In regard to the applied questionnaires from Bartneck et al. (2009b), internal consistencies of $\alpha > 0.8$ are achieved throughout all picture ratings.

5.2.2 Distance Behavior (Beam)

For the analysis of the frontal scenarios (first block), one 2-way MANOVA, comprising the frontal distance variation as a within-subjects variable and the human-likeness variation of Beam as a between-subjects variable, is assessed. In addition, for the analysis of the second block, a second 2-way MANOVA, containing the lateral distance as a within-subjects variable and Beam's human likeness as a between-subjects variable, is computed. Attained results are summarized in Table 5-4 and 5-5. It is important to note that, as in the second study, required statistical assumptions for applying MANOVAS had been tested. Since a large number of variables neither show variance homogeneity nor normally distributed data, the method of Geisser and Greenhouse is applied, taking into account possible violations of these assumptions, according to Bortz and Döring (1995). In addition, as in the second study, the method of Geisser and Greenhouse is also applied for the non-intervall scaled item *perceived proximity*.

Independent Variable	**Effect**	**F (df1,df2)**	**p**	**η²**
Frontal distance (FD)	**Perceived proximity**	**(3.17,39) = 54.99**	**<0.01**	**0.59**
	perceived spatial discomfort	**(2.95,39) = 24.76**	**<0.01**	**0.39**
	perceived motion acceptance	**(2.71,39) = 19.67**	**<0.01**	**0.34**
	expectation conformity	**(3.05,39) = 4.40**	**0.005**	**0.10**
	perceived safety	**(2.41,39) = 9.12**	**<0.01**	**0.19**
	perceived human likeness	**(4,39) = 2.54**	**0.04**	**0.06**
	perceived proximity compared to a human	**(4,39) = 40.34**	**<0.01**	**0.51**
Beam's level of human likeness (HL)	Perceived proximity	(1,19) = 0.02	0.88	0.00
	perceived spatial discomfort	(1,19) = 0.02	0.88	0.00
	perceived motion acceptance	(1,19) = 0.03	0.85	0.00
	expectation conformity	(1,19) = 0.002	0.96	0.00

	perceived safety	(1,19) = 1.02	0.31	0.02
	perceived human likeness	(1,19) = 0.97	0.33	0.02
	perceived proximity compared to a human	(1,19) = 0.29	0.58	0.00
FD x HL	Perceived proximity	(3.17,39) = 1.89	0.13	0.04
	perceived spatial discomfort	(2.95,39) = 0.59	0.61	0.01
	perceived motion acceptance	(2.71,39) = 0.95	0.41	0.02
	expectation conformity	(3.05,39) = 0.51	0.67	0.01
	perceived safety	(2.41,39) = 1.35	0.26	0.03
	perceived human likeness	(4,39) = 1.36	0.24	0.03
	perceived proximity compared to a human	**(4,39) = 2.61**	**0.03**	**0.06**

Table 5-4 analysis of the first block (significant effects are printed in bold)

In general, the analysis of the first block reveals significant main effects for all dependent variables due to frontal distance variations. However, the manipulation of Beam's level of human likeness leads to no significant influence on the captured dependent variables. Furthermore, only one significant interaction is obtained (see Table 5-4).

Independent Variable	**Effect**	**F (df1,df2)**	**p**	**η^2**
Lateral distance (LD)	**Perceived proximity**	**(2.87,39) = 56.27**	**<0.01**	**0.59**
	perceived spatial discomfort	**(2.96,39) = 25.79**	**<0.01**	**0.40**
	perceived motion acceptance	**(2.17,39) = 21.14**	**<0.01**	**0.35**
	expectation conformity	**(4,39) = 9.47**	**<0.01**	**0.20**
	perceived safety	**(3.06,39) = 12.28**	**<0.01**	**0.24**
	perceived human likeness	**(3.29,39) = 8.69**	**<0.01**	**0.18**
	perceived proximity compared to a human	**(2.89,39) = 32.84**	**<0.01**	**0.46**
Beam's level of	**Perceived proximity**	**(1,19) = 4.97**	**0.03**	**0.11**

human likeness (HL)	perceived spatial discomfort	(1,19) = 0.75	0.39	0.01
	perceived motion acceptance	(1,19) = 0.10	0.74	0.00
	expectation conformity	(1,19) = 0.58	0.44	0.01
	perceived safety	(1,19) = 0.09	0.75	0.00
	perceived human likeness	(1,19) = 0.49	0.48	0.01
	perceived proximity compared to a human	(1,19) = 0.09	0.76	0.00
LD x HL	**Perceived proximity**	**(2.87,39) = 3.19**	**0.02**	**0.07**
	perceived spatial discomfort	**(2.96,39) = 3.07**	**0.03**	**0.07**
	perceived motion acceptance	(2.17,39) = 2.33	0.09	0.05
	expectation conformity	**(4,39) = 2.99**	**0.02**	**0.07**
	perceived safety	**(3.06,39) = 4.32**	**0.006**	**0.10**
	perceived human likeness	(3.29,39) = 1.77	0.15	0.04
	perceived proximity compared to a human	(2.89,39) = 0.45	0.70	0.01

Table 5-5 analysis of the second block (significant effects are printed in bold)

Similar to frontal distance variations, the analysis of the second block (lateral distance scenario) shows significant main effects for all dependent variables due to the lateral distance manipulation. The altered human likeness level of Beam evokes one main effect this time. In addition, four significant interaction effects between the two factors occur. Thus, in contrast to block one, some of the assessed dependent variables are impacted by an altered human likeness of Beam.

Due to the non-interval scale level of the perceived proximity, two additional Friedman ANOVAs for frontal and lateral distances are computed. The Friedman ANOVA for the perceived proximity ratings of lateral distances reveals a Chi-square value of 95.43 which is highly significant ($p<0.01$). For frontal distances, the Friedman ANOVA reveals a Chi-square value of 99.81 which is also highly significant ($p<0.01$). Thus, the previously mentioned statistical decisions are supported.

All obtained mean scored and corresponding standard errors are charted in the following figures (see Figure 5-13 to 5-19). Their order corresponds to the tables 5-4 and 5-5. In figure 5-13, the perceived frontal and lateral proximity of Beam is shown.

How would you rate Beam's maintained frontal/lateral distance towards you?

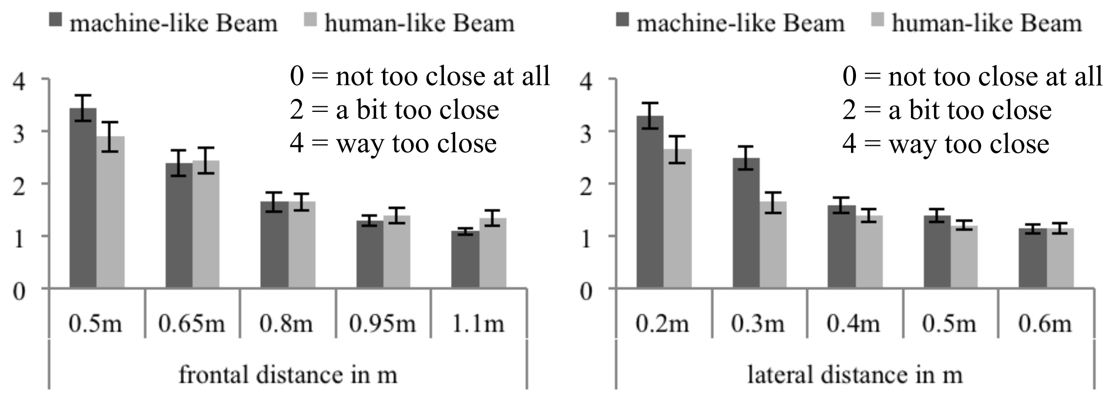

Figure 5-13 illustration of the perceived lateral and frontal proximity of Beam

In general, smaller frontal and lateral distances are rather perceived as way too close compared to greater distances. For frontal distances, post Bonferroni post-hoc tests show significant differences between all means except between 0.8m/0.95m, and 0.95m/1.1m. Beam's human likeness manipulation does not affect the ratings.

For lateral distances, significant differences occur between all means except 0.5m/0.6m. In addition, computed Bonferroni post-hoc tests show a significant differences between the machine- and human-like Beam (p=0.035). Figure 5-13 shows that the human-like Beam causes a lower perceived proximity than the machine-like Beam within all lateral trials.

Furthermore, frequencies of '*not to close at all*' ratings for frontal and lateral distances are assessed and are reported in table 5-6 and 5-7.

	human-like Beam					**machine-like Beam**				
Frontal distance in m	0.50	0.65	0.80	0.95	1.10	0.50	0.65	0.80	0.95	1.10
'*not too close at all*' ratings	3	5	10	14	15	1	5	8	14	18
percentage	15	25	50	70	75	5	25	40	70	90

Table 5-6 frequencies of not to close at all ratings for frontal distances

	human-like Beam					machine-like Beam				
Lateral distance in m	0.2	0.3	0.4	0.5	0.6	0.2	0.3	0.4	0.5	0.6
‘*not too close at all*’ ratings	3	12	13	16	16	2	4	10	13	17
percentage	15	60	65	80	80	10	20	50	65	85

Table 5-7 frequencies of not to close at all ratings for lateral distances

Attained findings regarding the perceived spatial discomfort are illustrated in Figure 5-14.

Did the chosen distance from Beam make you feel uncomfortable?

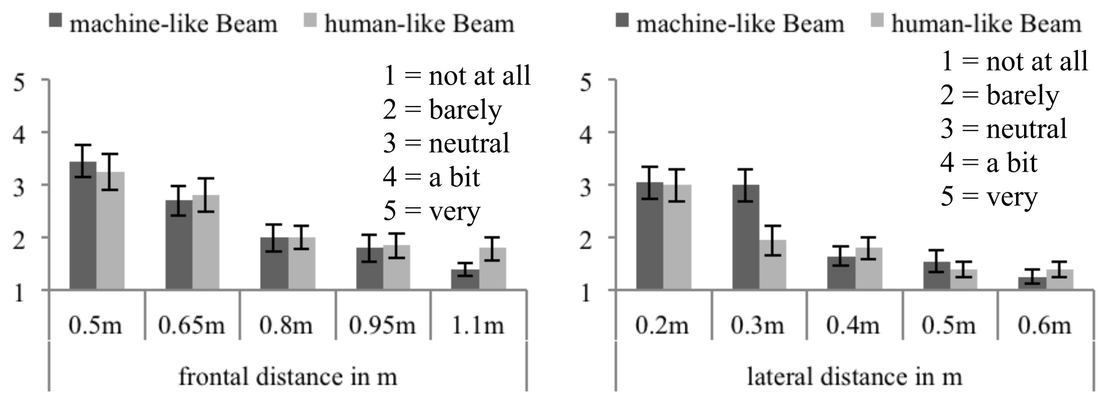

Figure 5-14 illustration of the perceived spatial discomfort

In general, the attained results show that greater maintained frontal and lateral distances lead to a decreased spatial discomfort. For frontal distances, significant differences occur between all means except 0.8m/0.95m, and 0.95m/1.1m. The analysis shows no significant effect for the human likeness manipulation of Beam.

For lateral distances, mean scores significantly differ between all distance variations except 0.2m/0.3m, 0.4m/0.5m, and 0.5m/0.6m. In addition, the two factors (lateral distance and beam’s level of human likeness) cause a significant interaction effect which reveals less spatial discomfort for 0.3m for the human-like version of Beam.

In the next figure, the assessed motion acceptance of frontal and lateral distances is charted (see Figure 5-15).

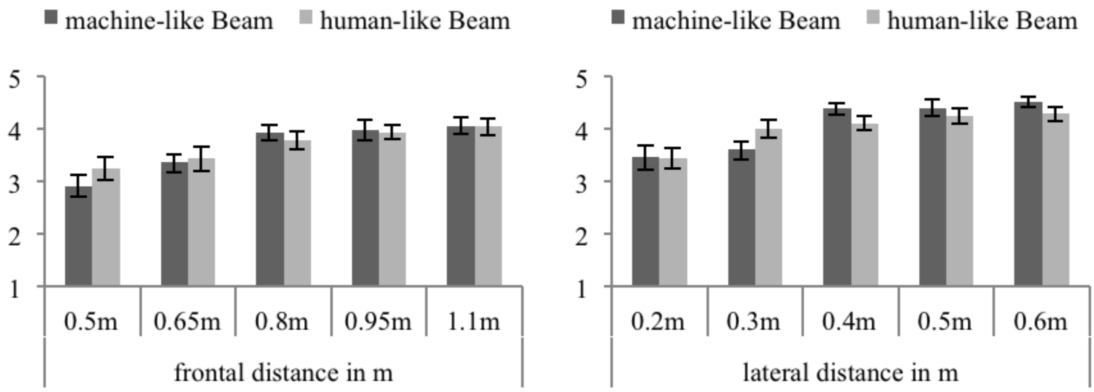

Figure 5-15 illustration of the perceived motion acceptance
(Rating scale: 1 = strongly disagree, 5 = strongly agree)

As in the second study, negatively poled items are re-coded and an overall mean comprising all six items is computed. Internal consistencies of $\alpha > 0.8$ are achieved for lateral and frontal distances. Powerful main effects are found for both distances variations showing an increased motion acceptance for greater maintained distances. For frontal distances, significant differences occur between all means except 0.5m/0.65m, 0.8m/0.95m, 0.8m/1.1m, and 0.95m/1.1m.

For lateral distances, post hoc tests show significant differences between all means except 0.2m/0.3m, 0.4m/0.5m, and 0.4m/0.6m, and 0.5m/0.6m.

No significant influence is obtained for the second factor (Beam's level of human likeness). Furthermore, no significant interaction effect occurs.

In Figure 5-16, the rated expectation conformity is plotted.

Beam's motion behavior was exactly like I expected it.

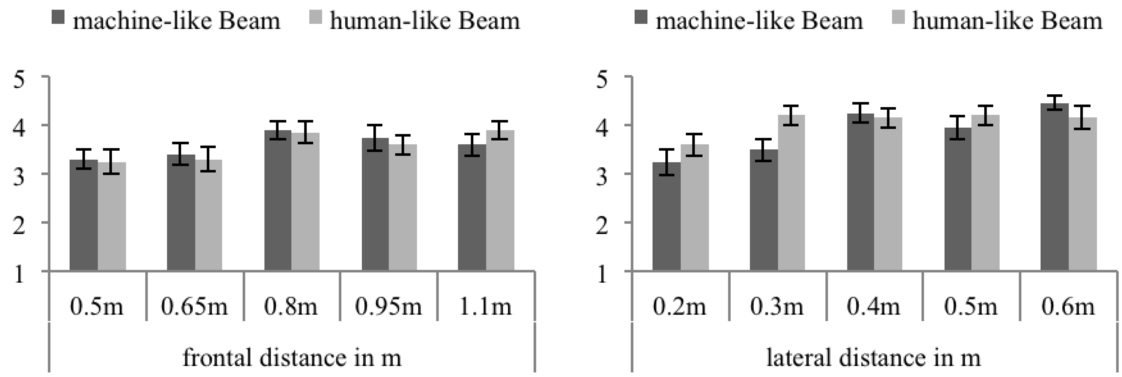

Figure 5-16 illustration of the perceived expectation conformity
(Rating scale: 1 = strongly disagree, 5 = strongly agree)

For frontal distances, charted results show that 0.8m met participants' expectations best. However, significant differences only occur between 0.5m/0.8m and 0.65m/0.8m. No significant influence is obtained for Beam's level of human likeness.

For lateral distances, significant differences are obtained for 0.2m/0.4m, 0.2m/0.5m, 0.2m/0.6m, and 0.3m/0.6m. In addition, a significant interaction effect is found between lateral distance and Beam's level of human likeness. A motion behavior involving smaller maintained distances (0.2m/0.3m) is less expected for a machine-like Beam than for a human-like Beam.

Ratings regarding the perceived safety around Beam are shown in Figure 5-17.

How safe did you feel around Beam?

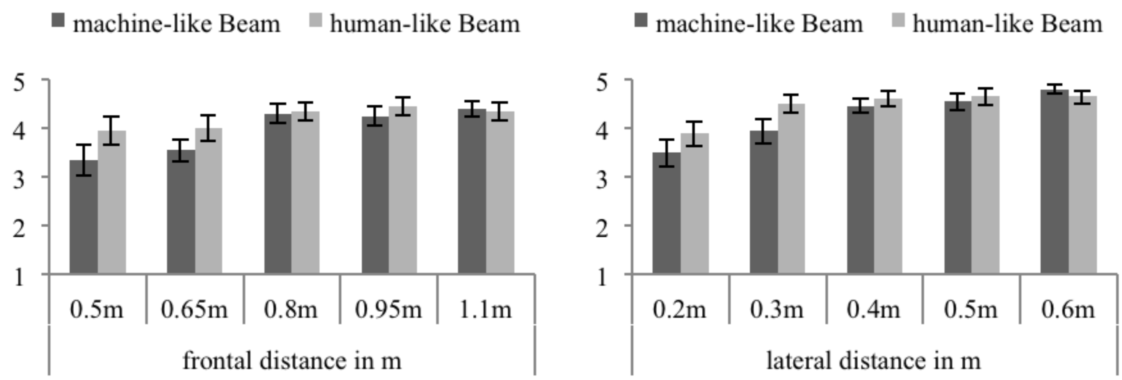

Figure 5-17 illustration of the perceived safety
(Rating scale: 1 = not at all, 5 = very)

In general, the perceived safety is higher for all greater maintained frontal and lateral distances. In particular, significant differences occur for all means within frontal distances except for 0.5m/0.65m, 0.8m/0.95m, and 0.8m/1.1m. Beam's level of human likeness has no significant impact.

For lateral distances, attained means significantly differ between 0.2m/0.3m, 0.2m/0.4m, 0.2m/0.5m, 0.2m/0.6m, 0.3m/0.6m, and 0.5m/0.6m. In addition, a significant interaction is found, primarily showing higher ratings of safety for a human-like Beam within smaller maintained lateral distances (0.2m/0.3m).

The following figure shows the attained ratings regarding the perceived human likeness of Beam's motion behavior.

How human-like was Beam's motion behavior?

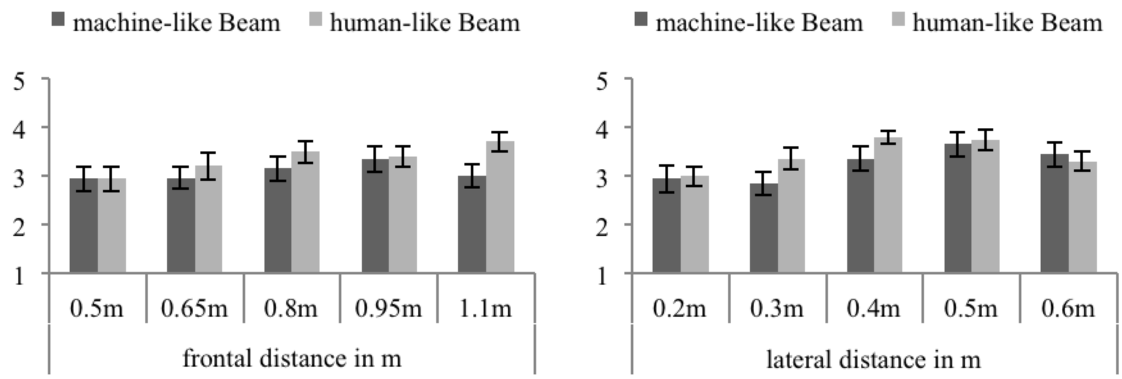

Figure 5-18 illustration of the perceived human likeness of Beam's motion behavior
(Rating scale: 1 = not at all, 5 = very)

For frontal distances, the post-hoc analysis reveals no significant differences at all. Furthermore, Beam's human likeness manipulation has no significant impact.

For lateral distance, significant differences occur for 0.2m/0.4m, 0.2m/0.5m, 0.3m/0.4m, 0.3m/0.5m, and 0.5m/0.6m. No significant influence of the second factor is found.

The last dependent variable is charted in the proximate figure 5-19.

Compared to a human in the same situation, Beam approached/passed by me?

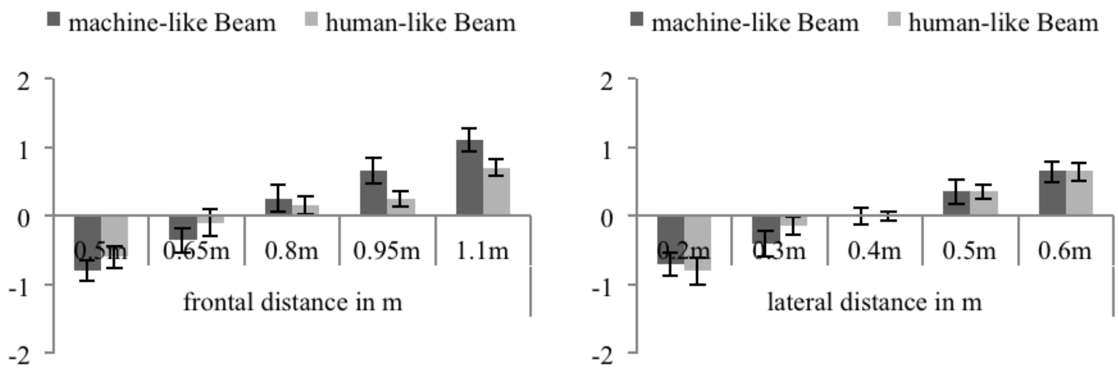

Figure 5-19 illustration of the perceived proximity compared to a human
(Rating scale: -2 = way closer, 0 = similar to a human, 2 = way farther)

For frontal distances, the post-hoc analysis reveals significant differences between all means, except 0.8m/0.95m. In addition, a significant interaction effect occurs for frontal distance and Beam's level of human likeness, showing that maintained distances by the human-like Beam are overall rated as more similar to a usual distance behavior of a human in the same situation.

For lateral distances, significant differences occur for all means except 0.3m/0.4m. Beam's level of human likeness has no significant influence.

Subsequently, multiple Pearson's correlations are run to determine the relationship between all dependent variables (Bortz & Döring, 1995). As in the second study, one Pearson's correlation is computed for each frontal and lateral distance manipulation. For each significant relationship between two variables, Table 5-8 shows the corresponding r_{min} and r_{max}. (r_{min} = the smallest assessed r score for this relationship, r_{max} = the greated assessed r score for this relationship). In literature, the following conventions for r are presumed: no relationship (0.01 to 0.19), weak positive relationship (0.20 to 0.29), moderate positive relationship (0.30 to 0.39), strong positive relationship (0.40 to 0.69), and very strong positive relationship (> 0.70). The same negative ranges account for negative relationships (Bortz & Döring, 1995).

Relationship	**r_{min}**	**r_{max}**
motion acceptance & spatial discomfort	-0.5	-0.85
motion acceptance & perceived proximity	-0.34	-0.68
motion acceptance & expectation conformity	0.63	0.78
motion acceptance & perceived safety	0.53	0.83
expectation conformity & human likeness	0.30	0.48
perceived proximity & spatial discomfort	0.37	0.83
spatial discomfort & perceived safety	-0.41	-0.80
spatial discomfort & expectation	-0.33	-0.64
safety & expectation conformity	0.34	0.68

Table 5-8 Pearson's correlations for all dependent variables
Note: only correlations with a two-tailed significance of $p < 0.05$ are reported

Lastly, potential influences of the captured control variables on each dependent variable are analyzed by computing 5 additional two-way MANOVAS with distance (frontal or lateral) serving as a within-subjects variable and one of the control variables serving as a between-subjects variable for each block. The MANOVAS do not show any significant impact. Thus, participants' sensations in terms of measured dependent variables are not significantly affected by participants' gender, cultural background, professional background, prior experience with autonomous systems, or prior experience with the applied Beam.

5.2.3 Comparison of Distance Findings of Study II and III

For comparing the attained results of study II with findings from study III, further MANOVAS are computed. One 2-way MANOVA, comprising the frontal distance variation as a within-subjects variable and robot type (transport assistant, machine-like Beam, human-like Beam) as a between-subjects variable over all dependent variables, is assessed. In addition, a second 2-way MANOVA, containing the lateral distance as a within-subjects variable and robot type (transport assistant, machine-like Beam, human-like Beam) as a between-subjects variable over all dependent variables, is computed. Attained results are summarized in Table 5-9 and 5-10. Again, required statistical assumptions for applying MANOVAS had been tested. Since a large number of variables neither show variance homogeneity nor normally distributed data, the method of Geisser and Greenhouse is applied, taking into account possible violations of these assumptions, according to Bortz and Döring (1995).

Independent Variable	**Effect**	**F (df1,df2)**	**p**	**η^2**
Frontal distance (FD)	**Perceived proximity**	**(3.2,78) = 96.02**	**<0.01**	**0.55**
	perceived spatial discomfort	**(3.3,78) = 51.98**	**<0.01**	**0.40**
	perceived motion acceptance	**(3.08,78) = 34.47**	**<0.01**	**0.30**
	expectation conformity	**(3.5,78) = 8.29**	**<0.01**	**0.09**
	perceived safety	**(2.9,78) = 18.71**	**<0.01**	**0.19**
	perceived human likeness	**(3.8,78) = 6.16**	**<0.01**	**0.07**
	perceived proximity compared to a human	**(3.6,78) = 65.27**	**<0.01**	**0.45**
Robot Type (RT)	Perceived proximity	(3,58) = 0.02	0.88	0.00
	perceived spatial discomfort	(3,58) = 0.23	0.78	0.00
	perceived motion acceptance	(3,58) = 0.03	0.96	0.00
	expectation conformity	(3,58) = 0.012	0.88	0.00

	perceived safety	(3,58) = 1.04	0.35	0.02
	perceived human likeness	(3,58) = 0.77	0.46	0.02
	perceived proximity compared to a human	(3,58) = 0.44	0.64	0.00
FD x RT	Perceived proximity	(6.4,78) = 1.11	0.33	0.02
	perceived spatial discomfort	(6.7,78) = 1.06	0.38	0.02
	perceived motion acceptance	(6.1,78) = 0.95	0.60	0.04
	expectation conformity	(7.02,78) = 0.64	0.72	0.01
	perceived safety	(5.9,78) = 1.23	0.28	0.03
	perceived human likeness	(7.6,78) = 1.26	0.26	0.03
	perceived proximity compared to a human	**(7.2,78) = 1.99**	**0.05**	**0.04**

Table 5-9 analysis for frontal distances (significant effects are printed in bold)

In general, the analysis reveals significant main effects for all dependent variables due to frontal distance variations. However, the manipulation of the robot leads to no significant influence on the captured dependent variables. Furthermore, only one significant interaction is found.

Independent Variable	**Effect**	**F (df1,df2)**	**p**	**η^2**
Lateral distance (LD)	**Perceived proximity**	**(3.1,78) = 82.37**	**<0.01**	**0.51**
	perceived spatial discomfort	**(3.2,78) = 51.69**	**<0.01**	**0.40**
	perceived motion acceptance	**(2.5,78) = 38.66**	**<0.01**	**0.33**
	expectation conformity	**(3.2,78) = 14.25**	**<0.01**	**0.15**
	perceived safety	**(3.1,78) = 21.81**	**<0.01**	**0.21**
	perceived human likeness	**(2.9,78) = 24.17**	**<0.01**	**0.23**
	perceived proximity compared to a human	**(3.1,78) = 57.13**	**<0.01**	**0.46**
Robot Type (RT)	**Perceived proximity**	**(3,58) = 6.86**	**0.02**	**0.09**

	perceived spatial discomfort	(3,58) = 0.96	0.38	0.02
	perceived motion acceptance	(3,58) = 0.06	0.93	0.00
	expectation conformity	(3,58) = 0.41	0.66	0.01
	perceived safety	(3,58) = 1.7	0.17	0.04
	perceived human likeness	(3,58) = 0.7	0.49	0.01
	perceived proximity compared to a human	(3,58) = 1.89	0.15	0.04
LD x RT	Perceived proximity	(6.3,78) = 1.99	0.06	0.04
	perceived spatial discomfort	**(6.4,78) = 2.04**	**0.04**	**0.05**
	perceived motion acceptance	(5.03,78) = 1.93	0.09	0.04
	expectation conformity	(6.4,78) = 1.62	0.13	0.04
	perceived safety	(6.2,78) = 1.11	0.35	0.02
	perceived human likeness	(5.8,78) = 0.99	0.43	0.05
	perceived proximity compared to a human	(6.3,78) = 0.32	0.93	0.01

Table 5-10 analysis for lateral distances (significant effects are printed in bold)

Altogether, the second analysis reveals significant main effects for all dependent variables due to lateral distance variations. In addition, a significant main effect for the perceived proximity within lateral distances occurs, and post-hoc comparisons show a significant difference on a significance level of α=0.05 between the transport assistant and the human-like Beam (p = 0.002). The difference between the machine- and human-like Beam is almost significant on a significance level of α=0.1 (p=0.12). The difference between the transport assistant and the machine-like Beam is not significant (p=1.0). Moreover, a significant interaction effect for the perceived spatial discomfort on a significance level of α=0.05 occurs, and two further significant interaction effects for the perceived proximity and motion acceptance are obtained on a significance level of α=0.1.

5.3 Discussion

In reviewing the primary goals of this study, it needs to be highlighted that by investigating the same research context of study II with another autonomously approaching or passing mechanoid (Beam), it is aimed to address one of the major challenges in the prevailing body of HRP research. Given variously existing incomparable findings due to a frequent application of diverse robots, this study primarily aims to validate previously attained outcomes and thus, intends to contribute to a higher level of findings' generality. Therefore, the conceptualized experimental methodology is aligned as much as possible to study II, permitting relatively robust and internally valid comparisons. In addition, this experiment empirically attempts to shed light on a potential influence of a robot's level of human likeness on subjects' distance preferences in a hallway.

To sum up the central findings, the picture rating reveals that the human likeness manipulation of Beam evokes a significantly more human-like, lifelike and liked robot perception, and the analysis also indicates that the machine-like version of Beam is significantly more human-like, lifelike and more liked than the transport assistant.

As in the second study, the varied frontal and lateral distances lead to significant effects for each measured dependent variable. Furthermore, almost all assessed effect sizes were large, which shows that the overall variance of the dependent variables is to an estimated large extent explained by the effect variance. Accordingly, the computed analysis suggests a general relevance of diversely maintained distances for an autonomously moving Beam in a hallway. In particular, results suggest an accepted frontal mean distance of approximately 0.8m towards an autonomously approaching machine- or human-like Beam since the analysis shows no significant effect of Beam's manipulation of human-likeness. Furthermore, the computed MANOVA comprising all employed robots (transport assistant, machine- and human-like Beam) reveals that no significant differences exist among the attained frequencies of *not too close at all* ratings. Therefore, findings show that no significant difference between the accepted frontal mean distance of study II and the one of this study exists, regardless of the applied robot type (transport assistant, machine-like Beam, human-like Beam). For lateral distances, the analysis shows that a more human-like robot significantly decreases subjects' lateral distance preferences by more than 0.1m (>0.2m, <0.3m) compared to the accepted lateral mean distance in study II (~0.4m), which is significant on a 5% level of significance between the human-like Beam and the transport assistant, and which is significant on an approximate 10% level of significance between the human-like and machine-like Beam. Though the machine-like Beam is perceived as significantly more human-like than the transport assistant, no significant influence on the averagely accepted lateral distance is observed.

Similar to study II, findings also show that Beam's distance behavior partly affects the overall motion acceptance. In particular an overshooting of averagely accepted distances should be avoided. All findings are more precisely discussed in the following paragraphs.

To discuss the first hypothesis of this study, the computed frequency of '*not too close at all ratings*' reveals that slightly more than 40% (machine-like Beam) and slightly more than 50% (human-like Beam) of all subjects do not rate a distance of 0.8m as *too close*. The computed MANOVA shows no significant main effect for the manipulation of Beam's human-likeness and post-hoc comparisons indicate no significant differences between 0.8m/0.95m. Though the attained findings for the machine-like looking Beam seem to align to findings of study II, the analysis shows that the difference between the two Beam versions is not significant. In addition, a second computed MANOVA comprising all employed robots as a between-subject variable reveals that the accepted frontal mean distance from study II is not significantly different from the one in this study. The variation in attained frequencies may occur due to individual differences in distance preferences or a measurement accuracy of 0.05m. Thus, the first hypothesis is supported and gained results suggest an accepted frontal mean distance that approximately corresponds to the one of study II (~0.8m).

In addition, this finding shows that the assessed accepted frontal mean distance of study I (~0.8m) holds true for the examined scenario in the present experiment, and for the one in study II as well. Consequently, a loss of locus-of-control does not seem to evoke a higher level of threat which in turn leads to desired greater frontal approach distances. Interestingly, this finding is not in accordance with previously suggested assumptions in the discussions of study I and II (see sections 3.3 and 4.3). Although Beam possesses a significantly smaller body size and rather appears fragile compared to the transport assistant, which has been found in HHP to reduce interpersonal distances due to the amount of perceived threat (Bailey et al., 1976), the accepted frontal approach distance is not significantly influenced. Hence, it seems reasonable to assume that the difference between the attained frontal mean distance in study II (>0.8m, <0.95m) and the assessed frontal mean distance in study I (~0.8m) is biased by the prevailing measurement accuracy or, more likely, by large individual differences in distance preferences. This finding also shows that a less voluminous and more fragile appearing Beam does not seem to induce a decreased amount of threat than a more bulky appearing transport assistant. Moreover, it is interesting to note that Beam's considerably taller height than the transport assistant does neither seem to influence the accepted frontal approach distance, which could have been assumed according to previous findings in HHP (e.g. Caplan & Goldman, 1981). Thus, the present work rather aligns to previous HRP studies (e.g. Koay et al., 2007) that have reported no significant influence of robot height on frontal distance preferences. Unfortunately, physical robot features, such as height and size, have neither been systematically nor thoroughly investigated in HRP yet. Accordingly, this should be subject of future research. Alternatively, this sort of robot design (Beam) might induce a decreased amount of threat, but it seems to be of minor relevance for a socially adequate frontal approach distance behavior. In sum, the comparison of study II and III indicates that the difference in the employed robots' level of human likeness, body size and height has no significant influence on subjects' frontal distance preferences in the examined research context, which in turn supports the first hypothesis.

Additionally, the greatest maintained frontal distance is not *too close* for 75% (human-like Beam) and 90% (machine-like Beam) of all subjects, and the smallest maintained frontal distance is only acceptable for 15% (human-like Beam) and 5% (machine-like Beam) of all participants. As shown by the computed MANOVA (no significant main effect for Beam's manipulation of human-likeness), the variation in the assessed frequencies is not significant and might occur due to individual differences. The analysis also reveals that gained ratings of the smallest as well as greatest maintained distance are significantly different from ratings of 0.8m. Thus, the relevance of maintaining a frontal threshold of comfort is also highlighted for another mechanoid (Beam), autonomously approaching a standing person in a hallway. Furthermore, the attained frontal mean distance generally is in line with the majority of previous HRP research again (e.g. Hüttenrauch et al., 2006; Brandl et al., 2013), suggesting the personal zone as the most suitable for frontal robot-to-human approaches.

Assessments of the perceived spatial discomfort demonstrate significantly higher ratings for the smallest maintained distance (0.5m) compared to the approximate mean distance (0.8m), and compared to the greatest maintained distance (1.1m). Moreover, the rating of the greatest maintained distance is significantly lower than the one of 0.8m. Thus, these ratings apparently correlate with gained proximity ratings, showing that a greater proximity also evokes more spatial discomfort, and vice versa. This is supported by computed correlations, showing significantly positive strong to very strong relationships between these two variables. Hence, obtained results suggest that an autonomously approaching Beam should avoid invading subjects' personal space in order to prevent feelings of discomfort.

In order to discuss the second hypothesis of this experiment, the data of the machine-like looking Beam is interpreted at this point. The computed MANOVA for the second block (lateral distances) shows a significant main effect for the manipulation of Beam, which is further discussed in the scope of the fifth hypothesis. Although the computed MANOVA comprising all employed robot types shows a difference between both Beams on a less strict significance level (p=0.12), the effect of Beam's altered human likeness on lateral distance preferences is seen as statistically relevant. With respect to postulations from Rothman (1990), it is assumed that the very conservative Bonferroni correction increases the risk of generating type II errors. Thus, the Bonferroni adjustment cannot decrease type I errors without inflating type II errors (Rothman, 1990). Both assessed significances between the two Beam versions (MANOVA comprising machine- and human-like Beam, p=0.035; MANOVA comprising all employed robots, p=0.12) do not largely vary from each other. The less significant result may occur due to the conservative Bonferroni correction. Therefore, only the data for the machine-like looking Beam is consulted at this point. The computed frequency of '*not too close at all*' ratings shows that half of the subjects (50%) perceive the previously gained accepted lateral mean distance of study II (~0.4m) as not *too close*. Accordingly, this result corresponds to attained findings from study II, which poses support for the second hypothesis.

Furthermore, a closer view to the frequency findings indicates that 85% of all participants do not perceive a personal space violation at 0.6m. In contrast, only 10% of all subjects still accept a lateral distance of 0.2m. Computed post-hoc tests reveal that these differences significantly differ from each other and from the accepted mean distance (~0.4m). Thus, as in the previous experiment, this study also validates the existence of accepted lateral mean distances for another autonomously passing mechanoid (Beam) in a hallway. Moreover, findings pose an initial exploration of lateral passing distances for Beam, and a second validation (upon study II) of previously accepted lateral mean distances (study I) for an autonomously passing mechanoid in a hallway. As already discussed in the second study (PeopleBot compared to transport assistant), a diminished body size of the mechanoid (Beam compared to transport assistant) or a more fragile appearance of Beam than the transport assistant seems to have no influence on accepted lateral passing distances, which is supported by the computed MANOVA comprising all employed robots and corresponding post-hoc tests (difference transport assistant/machine-like Beam, p=1.0). Furthermore, in line with frontal distance findings, the robot's height also seems to not influence subjects' lateral passing preferences in a hallway. Anyhow, it is crucial to note at this point that the present work does not explicitly investigate isolated effects of robot size or height and therefore, these indications remain hypotheses. The difference between the employed robotic systems (transport assistant and Beam) incorporates a wide range of diverse details, complicating an attribution of effects to one precise feature. In general, it is rather complicated to explore single outward features from a robot isolated from each other. For instance, the combination of a taller robot height and slimmer robot size can lead to an overall higher level of human likeness.

In regard to human-human proxemics theory, assumptions concerning an egg shape of personal space (e.g. Ashton & Shaw, 1980*)* seem to hold true for human-robot proxemics again. As in both previously conducted experiments of this dissertation, accepted frontal distances are approximately twice as large as lateral ones. However, as already mentioned earlier, future studies need to address directly approaching robot-to-human maneuvers from the side in order to validate this assumption.

Additionally, attained ratings of spatial discomfort also show, as for frontal distances, significant differences for both extreme distances (0.2m/0.6m) and the lateral mean distance (~0.4m). Furthermore, as already mentioned, strong positive correlations are assessed for the perceived proximity and spatial discomfort. Thus, the smallest maintained lateral distance evokes the highest spatial discomfort, and vice versa. Accordingly, this finding demonstrates the relevance to avoid lateral personal space violations in a hallway as well.

With regard to the third hypothesis, the overall motion acceptance ratings and corresponding post-hoc tests are analyzed. Attained ratings reveal that all smaller maintained frontal (0.5m, 0.65m) and almost all smaller maintained lateral distances (0.2m) than the previously accepted mean distances (frontal: ~0.8m, lateral: ~0.4m) lead to a significantly lower perceived motion acceptance. In contrast, maintained frontal and lateral distances surpassing the previously gained mean distances do not provoke a significantly higher perceived motion acceptance. Thus, the third hypothesis of this study is rather rejected than supported.

Accordingly, these results suggest that particularly distances below the accepted mean distances significantly decrease the overall motion acceptance. Instead, greater maintained distances than the mean distances do not cause significantly higher ratings. Thus, in terms of motion acceptance, maintaining frontal and lateral mean distances seems to be the most critical requirement for an autonomously moving robot. For frontal distances, results reveal that an overshooting of the frontal mean distance by 0.15m already negatively affects the motion acceptance. For lateral distance variations, an overshooting of the lateral mean distance by 0.2m already causes a significantly lower perceived motion acceptance. Nonetheless, neither frontal nor lateral examined test ranges can permit more precise interpretations regarding this relationship. Future studies, examining a finer varied distance range, should address this subject.

Furthermore, assessed strong to very strong negative correlations between motion acceptance and either the perceived proximity of Beam or the perceived spatial discomfort, additionally support the general conclusion that the proxemic behavior of Beam is also to some extent relevant for the overall motion acceptance. Particularly, frontal and lateral distances, which lead to a significantly higher perceived proximity and spatial discomfort than the mean distances, evoke a significant decrease of the motion acceptance rating. Anyhow, this effect is not observed in the contrary direction (greater distances than the mean distances). Nonetheless, these findings support, as findings of the second study, the general relevance of proxemics for the overall motion acceptance and thus, are also in line with the assumed general concept of the left hand side of the Uncanny Valley (Mori, 1970). However, as already pointed out in the second study, it cannot be assumed that desired distances in HRP are identical with those ones in HHP. Instead, it seems rather appropriate to assume that the underlying psychological motive, a desired avoidance of personal space violations in HHI, is also crucial to consider in HRP.

Nevertheless, this study cannot scrutinize the potential interplay of other motion features, such as speed or acceleration with proxemics. Thus, the precise relevance of an adequate distance behavior of an autonomously moving Beam for its overall motion acceptance cannot be determined by this study. Future studies should address this subject as well.

With respect to the developed fourth hypothesis, attained ratings indicate no support for the fourth hypothesis. In particular, computed t-tests show that higher ratings of human likeness and likeability for the human-like version of Beam are almost significant at a significance level of $\alpha=0.1$. Rating differences in the assessed animacy of both Beam versions show significance at a level of $\alpha=0.05$. Thus, in line with a more human-like and likeable rating, the human-like version of Beam is also rated as more lifelike. However, the attained results for human likeness and likeability are less confident than the ones for animacy ($p\sim0.1 > p=0.05$). By considering the manually adjusted significance level of $\alpha=0.01$, none of the assessed rating differences are significant and thus, this hypothesis needs to be rejected. Consequently, the attained results show no support for the general concept of the left hand side of the Uncanny Valley (Mori, 1970) and corresponding static relations of a robot's human likeness and the resulting effects on participants' impressions. On the other hand, results align to previous research (e.g. Bartneck et al., 2009a), indicating that the originally proposed concept of familiarity by Mori (1970) seems to be less appropriate or indeed inadequately translated into English. In addition, the attained ratings might suggest that the conducted human likeness manipulation of Beam has no significant effect to subjects when presented in pictures.

By contrast, the attained picture ratings shows that the machine-like Beam causes a significantly higher perception of human-likeness, likeability and animacy than the transport assistant. This result is of particular interest for the present work for two reasons. First, the analysis shows that a rather less bulky and more fragile appearing mechanoid (Beam) leads to a higher likeability than a more voluminous and cubic-like mechanoid (transport assistant). Additionally, the outward appearance of Beam is also rated as more human- and lifelike than the transport assistant. Most likely, the less cubic-like form of Beam and its abstractly appearing 'legs' may cause this effect. In addition, the more human-like height of Beam may also evoke a more human-like appearance. Indications for this effect have already been observed in a previous study by Koay et al. (2007), who have found that subjects generally perceived a tall machine- or human-like PeopleBot as more human-like compared to its identical smaller counterparts. Accordingly, along this line of thinking, it can be assumed that a robot's body height might be advantageous for generating positive impressions as long as the height does not overshoot the height of the opposing person. However, this subject needs to be more thoroughly investigated in the future. Moreover, a less bulky and more human-like appearing mechanoid receives higher ratings of likeability, which might be important for an overall product acceptance. Second, these findings pose evidence for the previously stated assumption that physical robot features, contributing to a robot's level of human likeness, play no relevant role for subjects' frontal distance preferences. However, subjects' lateral distance preferences are influenced by the altered outward robot design, which is discussed in the scope of hypothesis V.

In regard to methodological issues of this investigation, numerous points need to be addressed. First, the presented pictures do not have a very high quality (see questionnaires in Appendix G), which might cause a more complicated recognition of the projected real human face on Beam's screen. Possibly, this may bias the human likeness ratings of the machine- and human-like Beam, resulting in a non-significance on a level of $\alpha=0.01$.

Second, a presentation of the robots in pictures was necessary due to the desired comparison with the previously applied mechanoid (transport assistant), which was not available in the research facility of Bosch in the USA. In order to keep the robot presentation consistent, it was decided to present all robots in pictures. However, it remains open whether a presentation and rating of real non-moving robots would have caused diverse ratings. This could be addressed in future research.

Third, the human likeness manipulation of Beam poses a novelty in human-robot proxemics studies. As already noted in the theoretical foundation, to date, the existing body of research regarding the influence of human likeness on personal space is very small. Nonetheless, it is interesting to note that the previously conducted studies, examining this context (Butler & Agah, 2001; Koay et al. 2007), rather manipulated the robot's physical properties by adding arms or even a whole new robotic head to the robot's body. In contrast, the applied human likeness manipulation in the present experiment does not involve an alteration of Beam's physical properties at all. In future studies, researchers should address this subject to explore the type of human-likeness manipulations and its effect on people's sensations.

Fourth, the utilized method purposely captures multiple possible y-axis constructs in regard to the Uncanny Valley, which have been proposed in previous studies. As stated in the theoretical part of this dissertation (see section 2.5), various uncertainties regarding the most appropriate y-axis dimension for the Uncanny Valley exist. In line with assumptions of Bartneck and his colleagues (2009a), obtained results indicate that likeability might be a more suitable concept than familiarity (lower p value). Furthermore, the non-significant findings of uncanniness are not supporting previously mentioned approaches that pursued this method (Oehl et al., 2013). However, it needs to be highlighted that the present method works with non-moving pictures and is therefore incomparable to the previously applied method that has shown videos of robots (Oehl et al., 2013). Importantly, reviewed literature regarding the y-axis has revealed an enormous variety of methodological shortcomings and should therefore be addressed in the future as well.

Fifth, by utilizing the evaluated questionnaires of Bartneck et al. (2009a), this study poses a further validation of those and also provides a further translation into another language. Similar to previous evaluations, findings show good internal consistencies for all applied GODSPEED questionnaires.

Altogether, it can be stated that the experimental manipulation of Beam's human likeness evokes no significantly higher perceptions of human likeness, likeability, animacy, familiarity and uncanniness for the human-like Beam compared to the machine-like Beam. Nonetheless, the study sheds some light on the vague body of suitable y-axis concepts for the Uncanny Valley. Moreover, the picture rating provides a relevant insight into the effects of a robot's physical design. In particular, the analysis shows that the human-like and machine-like version of Beam leads to higher ratings of human likeness, likeability and animacy than the transport assistant and thus, indicates that a less voluminous robot size and taller robot height may contribute to a higher level of human likeness.

With respect to hypothesis V, the last part of this discussion addresses the assumed influence of Beam's human likeness manipulation on accepted frontal approach and lateral passing distances. As already noted, the computed MANOVA reveals not a single main effect due to Beam's human likeness manipulation for accepted frontal distances. However, one significant interaction effect for the perceived proximity compared to a human is obtained, which is addressed in the scope of the overall discussion (see section 6). Moreover, the computed MANOVA for the first block (frontal distance), comprising all employed robots of the present work, neither shows any main effect. Therefore, half of the predicted assumptions regarding hypothesis V are rejected at this point. Consequently, this finding is not in any accordance with previous research (Butler & Agah, 2001; Koay et al., 2007). In contrast to a previously reported increase in frontal distance preferences by a higher level of human likeness (e.g. Koay et al., 2007), the present results show no effect at all. Nonetheless, this result can be seen as a further indication that a more human-like robot appearance does not simultaneously demand a more human-like distance behavior, which has been already shown by (Butler & Agah, 2001; Koay et al., 2007). Furthermore, this overall result suggests that although a robot's level of human likeness leads to more positive impressions, it does not significantly influence accepted frontal mean distances. Thus, the gained frontal mean threshold of comfort (~0.8m) in a hallway seems to be valid for each employed robot in this project, which in turn poses a high generality of this distance finding.

Contrarily, the second computed MANOVA, comprising lateral distances as a within-subjects variable, shows a significant main effect for the perceived proximity due to Beam's human likeness manipulation. By analyzing the single mean scores of proximity ratings for each tested lateral distance, the human-like version of Beam consistently receives a lower rating than the machine-like one. Computed post-hoc comparisons show significant differences between 0.3m/0.4m and 0.4m/0.5m. Additionally, the assessed frequency of '*not too close at all ratings*' reveals an accepted mean distance at 0.4m (50%) for the machine-like Beam. In contrast, the same distance is already fine for 65% of the subjects in the human-like Beam scenario. As shown in Table 5-7 and according to the assessed distribution, the accepted lateral mean distance is already surpassed at 0.3m (60%), and a significant difference between 0.2m and 0.3m occurs. Thus, gained data shows that an increased human likeness manipulation leads to a decrease of accepted lateral mean distances by more than 0.1m. Accordingly, this part of hypothesis V, predicting an increase of lateral mean distances due to a more human-like Beam, is rejected as well. Furthermore, a significant interaction effect between lateral distance variations and Beam's level of human likeness occurs for the perceived spatial discomfort. Findings show that at 0.3m the perceived discomfort was significantly lower in the human-like Beam scenario. This finding is in accordance with previous observations, regarding a strong positive relationship between a lower perceived proximity and a lower perceived discomfort.

Taken together, this finding poses the first empirical indication regarding the effects of a robot's human likeness on lateral passing distance preferences. Importantly, the second computed MANOVA, comprising all applied robots in the present work, shows that significant differences only occur between the human-like Beam and both other robots. Thus, although the machine-like Beam is rated as more human-like than the transport assistant, no significant difference in lateral distance preferences is observed. Accordingly, the human likeness manipulation of the human-like Beam seems to comprise a critical difference leading to this significant influence. It can be assumed that the critical difference is based on the projected real human face on Beam's screen, incorporating real human eyes. Potentially, subjects have a higher level of trust towards a passing maneuver of a robot which possesses known and easy detectable anatomic features, permitting the robot to perceive its environment. Therefore, subjects may rather rely on the robot's ability to safely pass by them and not collide with them, which may be also related to a lower level of induced threat.

Interestingly, although subjects were aware of the projected character of the human eyes and the autonomy of Beam, the presence of human eyes on a robot seems to evoke underlying expectations, which is in accordance with previously stated assumptions regarding robot appearance and human expectations (Woods, 2006). Thus, this finding supports previous postulations of Lee et al. (2005), Powers and Kiesler (2006) and Woods (2006), suggesting that people unconsciously create a plausible mental model of robots based on the physical appearance. Therefore, the present work also highlights the importance of an adequate outward robot design for avoiding misleading expectations or unrealistic predictions about the robot's future behavior. Though equipping a social robot with human-like eyes may be beneficial for saving lateral passing space, roboticists should only apply this sort of design adaption when a robot's ability to socially navigate aligns to the performance of humans. Whether this effect would also occur for stylized human eyes should be researched in the future. Additionally, it remains open whether an even more human-like Beam would lead to a further decrease of accepted lateral mean distances. Future studies could address this subject by additionally equipping Beam with arms.

Nonetheless, the question remains *why Beam's human likeness manipulation exclusively evoked decreases in lateral distance preferences?* Several possible reasons are considered. First, as already stated in HHP (e.g Ashton & Shaw, 1980) and also suggested by previous studies of the present work, the frontal zone of personal space is greater than the lateral one. However, it needs to be considered that the robots in the present work do not directly approach participants from the side. Instead, the robots pass by them in diverse lateral passing distances. Thus, as already noted, the perceived level of threat could be significantly lower in lateral scenarios than in frontal ones. Given a well-predictable and non-colliding course in lateral trials, and an additionally more human-like appearance, subjects' may perceive less threat and more trust than in scenarios comprising the machine-like Beam. Due to the collision course in frontal trials, subjects may generally perceive high levels of threat, independently of robot's level of human likeness. Frontal collisions also happen between humans, which may increase the general level of alertness when people are confronted by frontally approaching humans, animals, or robots. Accordingly, these findings seem to support the validity of the *Dosey-Meisels Protection Theory* for a HRSI.

Second, the human likeness manipulation of Beam involves a real, but unfamiliar human face. Thus, participants had not known this face prior to the experiment. Though personal space zones refer to direct interaction scenarios (Hall, 1966), it is questionable whether they might also apply to the examined context. If this concept can be applied to a HRSI scenario, participants may treat the human-like Beam as a strange person, resulting in similar frontal distances compared to an unfamiliar, machine-like Beam or transport assistant. Importantly, the postulated zones by Hall (1966) have not been investigated for lateral personal space zones and no comparable lateral passing distance from HHP have been explored to date. Potentially, the familiarity of the confederate's face is not relevant to participants when they were passed by it, because they would also let a strange human pass by closer. Future studies could investigate this assumption by varying the familiarity of the projected face on Beam's screen. In addition, a future follow-up study could also intend to validate these findings by using a rather stylized human face.

However, it remains questionable why the conducted human likeness manipulation does not lead to increased frontal distances preferences, as found in previous HRP experiments (Butler & Agah, 2001; Koay et al., 2007). By considering previous findings in HRP, revealing the influence of mutual gaze on distance preferences in human-robot scenarios (Takayama & Pantofaru, 2009; Mumm & Mutlu, 2011), a possible explanation is posed by the precise experimental procedure of the present study. According to previous findings, the mutual gaze between the confederate and the subjects during frontal trials should have evoked increased distance preferences. Importantly, in the present experiment, the confederate directed his gaze away from the subjects' eyes shortly before he initialized the stop maneuver of Beam. In favor of maintaining the frontal distances as accurate as possible, the confederate needed to focus on the down-facing camera of Beam. Though mutual gaze was established again shortly after stopping Beam, this could serve as a possible explanation. Nonetheless, this subject demands further research attention in the future.

In sum, the above discussed findings suggests that a more human-like appearance of a robot poses a relevant practical benefit for twofold reasons: Positive impressions toward the robot and a reduced lateral approach distance by equipping the robot with human-like eyes, which can be advantageous for socially or spatially dense environments the robot shall operate in. Furthermore, based on the present data, it can be assumed that a robot with visible eyes induces a higher level of trust and a lower level of threat to standing persons in a hallway the robot is about to pass. However, no effects are observed for frontal approach distances, which is controversy compared to previous HRP studies (Butler & Agah, 2001; Koay et al., 2007) that have shown greater desired frontal approach distances towards more human-like robots.

In regard to specific details of the conceptualized method of this study, it can be highlighted that it is essential to mute the confederate throughout the entire experiment. Previous research has revealed that different voices significantly affect frontal approach distances (Walters et al., 2008b). Since the machine-like version of Beam has no voice, it was relevant to not implement a voice for the human-like Beam in order to avoid biases and confounders, and increase comparability. In addition, it was also relevant to ensure a consistent level of familiarity of the projected face for the entire sample. As already noted in HHP, the level of familiarity influences interpersonal distances (Hall, 1966) and was therefore assumed to potentially bias the present context as well. A further important methodological detail addresses the cultural difference. Most of the subjects were either US American or Germans and computed MANOVAS reveal no significant differences for all dependent variables. Thus, this result poses an empirical evidence in human-robot proxemics, supporting the postulated cultural classification of North Americans and Northern Europeans into non-contact cultures (e.g. Nanda & Warms, 2010). In addition, this is a relevant outcome for further interpretations in the overall discussion, which are based on inter-study comparisons.

5.4 Conclusion

To conclude, this study also highlights the general relevance of an adequate proxemic behavior for an autonomously approaching or passing robot in a hallway. The accepted frontal mean distance in study II is not significantly different from the one in this study (~0.8m). Attained differences in the computed frequencies of *'not too close at ratings'* can be seen as noise and may occur due to large individual differences on spatial preferences. Thus, this final study highlights the relevance of the assessed frontal mean threshold of comfort in study I (~0.8m), and in turn indicates that the simulated autonomy of the approaching robots as well as their different physical appearances (e.g. size, shape, human likeness) do not significantly affect subjects' frontal distance preferences in a hallway. Thus, the accepted frontal mean distance in the first study is valid for the same context with a different autonomously moving robot (Beam) as well, which increases the level of generalizability of this finding. Hence, this finding poses an advantageous empirical indication for the comparability and generality of previous HRP studies on accepted frontal approach distances that have often worked with very different robots.

Likewise, subjects' lateral distance preferences are neither significantly influenced by the robots' simulated autonomy, but are to some extent affected by the robot's level of human likeness. Only the human-like version of Beam significantly decreases subjects' lateral distance preferences. It is assumed that accepted lateral passing distances significantly decrease due to a projection of a real human face with human eyes on Beam's screen, which seems to support previously noted effects of robot appearance on human expectations. The more machine-like looking robots (transport assistant and machine-like Beam) lead to the same lateral distances preferences as in study I (~0.4m). Interestingly, this finding poses a novel discovery in HRP research. Nonetheless, it is important to note that these findings are exclusively relevant in the confines of this dissertation to date. In order to expand the state of knowledge, this phenomenon should be subject of investigation in future studies.

Furthermore, in favor of large individual differences in personal space, frontal mean distances of 1.1m and lateral mean distances of 0.6m are suggested in order to avoid personal space violations for the majority of subjects. Similar to the attained findings in the second study, these distances ensure an avoidance of spatial discomfort for the largest majorities of subjects, which is of high practical implication. Moreover, these results might also be of particular interest for existing and future robotic telepresence companies in order to design a more accepted spatial interaction (Cosgun, Florencio & Christensen, 2013). Nonetheless, future research should examine whether these distances are affected by other variables (e.g. by robot speed, habituation or an increased robot familiarity), or whether greater distances would be even more appropriate.

Another conclusion is that roboticists should at least ensure to design a proxemic behavior of an autonomously moving robot in a hallway that does not overshoot the accepted lateral mean distance by more than 0.1m, and the accepted frontal mean distance by more than 0.15m in order to avoid significant decreases of the perceived motion acceptance. However, the precise level of relevance of a robot's proxemics behavior for the overall motion acceptance cannot be completely derived from the obtained data. Thus, future studies should further address this subject.

Lastly, this study cannot unveil insights into possible habituation effects which have been uncovered in past research (e.g. Koay et al., 2007; Walters, et al., 2011). Consequently, in line with results of study II, suggested distances are appropriate for designing a socially acceptable robotic distance behavior in a hallway for first contact situations between people and robots.

6 Overall Discussion

In this chapter attained findings and the corresponding methodological approach is discussed and interpreted in the scope of all conducted studies. According to the overarching research questions of this dissertation, this chapter summarizes central findings and discusses its limitations. In addition, suggestions for future investigations are presented.

A crucial requirement of this doctoral project for contributing reliable, valid and thus, robust results to the existing scientific body is constituted by a systemically conceptualized empirical methodology. Furthermore, applied methodological approaches are highly similar to each other in order to ensure comparable and interrelatable findings throughout the three conducted studies. Several key aspects, regarding the pursued approaches of the present work, are summarized and discussed in the following paragraphs. They pose an essential foundation for permitting successive interpretations of the attained results.

In retrospect, as reviewed in the theoretical foundation, a general existence and relevance of a socially adequate distance behavior for avoiding feelings of discomfort has been shown by previous proxemic research, which has investigated appropriate distance behavior between humans (e.g. Hall, 1966), and between humans and robots (e.g. Walters, 2008). As frequently mentioned throughout this dissertation, however, only some of these works have provided a reliable and comparable empirical starting base for evaluating robotic proxemic behavior in a hallway. In particular, systematic and statistical relevant human-robot proxemics investigations, generally focusing on a hallway and specifically on accepted lateral passing distances, had not been conducted before the present research project. Hence, the present method poses the first systematic exploration in HRP research regarding these issues.

In particular, the empirical work of this dissertation starts off by putting a mechanoid (transport assistant) in control of the participants, requesting them to directly control acceptable approach and passing distances in a hallway based on their own arousing feelings of discomfort. Towards exploring the influence of robot speed on people's distance preferences, two different speed levels are varied in the first study (mechanoid in control of the subjects). Unfortunately, the possible range of variance was limited by the mechanoid's technical possibilities. It is important to ensure an accurate and consistent exposure throughout all experimental trials for obtaining reliable results. Therefore, the employed mechanoid (transport assistant) was operated with a maximum speed of 0.8m/s. A second speed level was set to 0.6m/s. Since lower speed levels than 0.6m/s have been already reported as too slow (Butler & Agah, 2001; Pacchierotti et al., 2005, 2006), the practical relevance would have been very low. Thus, a speed variation comprising two speed levels (0.6m/s and 0.8m/s) was realized, and this sort of variation had not been tested before to date.

Additionally, all trials were repeated in order to consider already proven habituation effects (e.g. Walters et al., 2011). Attained results provide accepted frontal and lateral mean distances, and permit subsequent derivations of hypotheses and distance ranges for a validation of these findings with autonomous robots. In a follow-up study (study II), the same mechanoid (transport assistant) autonomously maintained various distances in the same hallway, and participants' subjective sensations were recorded by utilizing questionnaires. In a comparitive study (study III), the transport assistant was replaced by another mechanoid (Beam), while other core details of the study, such as examined distances, instructions, questionnaires, the tested environment (hallway) and the robot's speed were not altered at all. In both studies, participants were not in control of the robots. In addition, applied questionnaires captured a wide range of variables, such as perceived proximity, safety, spatial discomfort, expectation conformity, motion acceptance or human likeness that permit interpretations regarding distance preferences and corresponding psychological motives in this sort of HRSI. The questionnaire, assessing the motion acceptance of a robot, poses the first systematic approach for measuring this construct that is of high importance in HRI, and satisfying Cronbach's alpha values are obtained.

Concerning the picture rating in the third study, the pursued approach utilizes previously elaborated questionnaires for measuring human likeness, likeability and animacy (Bartneck et al., 2009b). Hence, these questionnaires are further evaluated by the present work. In addition, two proposed constructs (familiarity, uncanniness) of the Uncanny Valley (Mori, 1970) are measured. Therefore, this approach provides further methodological experience for the rather uncertain body of knowledge regarding the relation of a robot's human likeness and corresponding attitudes/impressions (Bartneck et al., 2009a; Zlotowski et al., 2013).

Additionally, the conceptualized method for manipulating Beam's level of human likeness poses a novel approach in HRI. By using a telepresence robot (Beam), it was simple to alter Beam's screen from black to a real human face. Instead, previous work has manipulated the physical shape of robots by adding mechanistic arms or heads to their mechanistic bodies (e.g. Koay et al., 2007). In addition, the applied method considers the level of familiarity of the projected face, and great care was taken that none of the participants had known the confederate prior to the experiment. Therefore, a potential risk of biased results is avoided.

Taken together, this methodological approach poses a novelty in existing HRP research. The evaluation, comprising autonomous robots, is based on behavioral data from the first study, which was recorded with a higher level of reliability (laser scanner) compared to some previous studies that have based their distance measurements on floor markings (Walters et al., 2006) or subsequent video analysis (Walters et al., 2008b). Moreover, the applied control method of the mechanoid in the first study was easily mastered by all subjects and ensured a real stopping of the robot, which was also ensured by the applied method in study II and III. This method is assumed to lead to a more realistic sensation for participants. In contrast, many previous experiments have worked with Comfort Level Devices (Koay, Dautenhahn, Woods & Walters, 2006; Koay et al., 2007). Methods, involving those devices or similar techniques, do not stop the robot upon participants' indications and also limit the robots' frontal approach distance due to safety constraints (Koay et al., 2007), which may bias subjects' distance preferences. Thus, the utilized methods in the present work avoid this problem.

In addition, a further novelty of the elaborated method is posed by introducing a new working standard for HRP. It has been proposed by Walters (2008) that the distance between the closest static body parts of a robot and a human should be measured. However, he and his colleagues took the participants' feet as a reference point. In the present work, diverse biometrics of humans are considered by relying on laser measurements (study I) and participants' positions adjustments (study II and III) based on their belly/hip region. Thus, it is assumed that this novel approach in HRP considers observed effects of people's body size on personal space more appropriately (Lerner, 1973). Moreover, a wide range of further crucial methodological details, of which some have often differed or have not even been reported in previous research, are considered and consistently applied, such as a consistent distance between robots' and subjects' starting positions, consistent robot-to-human approaches, same level of robot speed and acceleration, consistent non-verbal/non-physical interaction context, the same level of distance accuracy (0.05m) for the autonomous distance management due to the simulated autonomy (study II and III), the same examined distance intervals (study II and III), and the same instructions (study II and III).

A further methodological advantage is posed by a precise consideration and recording of potential confounding variables. Though an enormous body of influencing factors on proxemics has already been widely studied and reported in human-human (e.g. Sommer, 1969, 2002a) and human-robot proxemics research (e.g. Takayama & Pantofaru, 2009; Mumm & Mutlu, 2011; Eresha et al., 2013; Duncan & Murphy, 2013), numerous HRP experiments have not reported crucial sample properties, such as cultural background (e.g. Hüttenrauch et al., 2006; Takayama & Pantofaru, 2009) or prior robotic experience (Walters et al., 2008b). It is of particular relevance for the comparison of study II and III that greatest care was taken to ensure a sample selection, involving comparable cultural backgrounds (non-contact cultures: Germans and North Americans). US Americans and Germans are assigned to non-contact cultures (Hall, 1966; Watson, 1970), which provides a reasonable theoretical foundation to compare findings across the conducted studies in this thesis. Moreover, the statistical analysis shows no significant influence of the cultural background on subjects' distance preferences. In addition, precise attention was paid to ensure a balanced level of gender for all samples, a similar age range (adults), a similar level of familiarity with robots and particularly with the employed robots, and a similar level of subjects' professional background. Computed unpaired t-tests confirm the similarity of the different samples (see Appendix C). Moreover, several other situational characteristics, which have been reported to influence personal space (e.g. lightning), were kept as consistently as possible.

Furthermore, in regard to past HRP research, a prominent challenge is posed by a further, largely varying study detail: the use of many incomparable robots. Given many diversely available robotic research platforms and many different research institutions, which are often confronted with limited financial opportunities, this problem will likely exist in the foreseeable future as well. However, by utilizing completely different robots, such as PeopleBot (Walters, 2008), PR2 (Takayama & Pantofaru, 2009), or Asimo (Kamide et al., 2014), in addition to many other differing study details, these experiments are hard to compare with each other, which in turn complicates a progressive development of findings' level of generality. Similar to Walters (2008), this work also examines distance effects in relation to the same mechanoid (transport assistant), which is beneficial for a higher comparability of these studies (study I and II). In contrast to previous research, the pursued method firstly aims to shed light on the potential effect of completely diverse mechanoids (transport assistant and Beam). As already mentioned, by aligning various study details of the third experiment (Beam) as close as possible to the second one (transport assistant), the conceptualized method permits more reliable and comparable insights into potential differences based on different robots.

To sum up, by considering, recording and implementing all these details as consistent as possible, the entire methodological approach of this work is seen as advantageous for achieving more replicable, reliable, valid, comparable and generic results.

With respect to the first central research question of this dissertation – *Do frontal and lateral spatial thresholds of comfort exist during a human-robot spatial interaction in a hallway?* – obtained results of the entire project confirm this question. In reviewing either study I (non-autonomous robot) or study II/III (autonomous robots), the existence of accepted frontal and lateral mean distances (= spatial thresholds of comfort) is empirically proven for a HRSI in a hallway. The assessed frontal and lateral mean thresholds of comfort are attained based on subjects' motives to avoid feelings of discomfort. Likewise, smaller maintained distances than the accepted mean distances lead to significantly increased indications of perceived spatial discomfort, which is additionally supported by strong positive correlations between perceived proximity and perceived discomfort. Thus, attained results also support previous assumptions regarding the relevance of a robot's socially adequate distance behavior for avoiding disaffected people (e.g. Pacchierotti et al., 2006; Walters, 2008; Mumm & Mutlu, 2008; Brandl et al., 2013).

In regard to the next central research questions of this dissertation, the primary objective is to explore precise distance values for frontal and lateral thresholds of comfort in a hallway. Based on postulated personal space zones and shape in HHP (Hall, 1966; Ashton & Shaw, 1980), and most comparable accepted frontal approach distances in HRP (Brandl et al., 2013), a greater accepted frontal mean distance than 0.46m, in addition to a smaller accepted lateral mean distance than the frontal one, is assumed. Given the assessed frontal (~0.8m) and lateral (~0.4m) mean distances in the first study, both assumptions are supported. In the two corresponding follow-up studies, it is aimed to validate these distances for autonomously approaching or passing robots. The developed hypotheses and selected distance intervals are based on the previously attained mean distances and on the cumulative frequency distributions of study I. It is assumed that accepted mean distances towards autonomously moving robots should correspond to the accepted mean distances from the first study, and findings reveal that this assumption is supported. Though the accepted frontal mean distance toward the transport assistant slightly increases in study II, the final analysis comprising all employed robots of the present work reveals that this increase is not significant.

In sum, findings indicate that accepted frontal mean distances and accepted lateral mean distances are not significantly influenced by a robot's simulated autonomy. Thus, the assessed spatial thresholds of comfort in study I (frontal: ~0.8m, lateral: ~0.4m) are also valid for the autonomously approaching or passing mechanoids (transport assistant/Beam). Accordingly, this finding suggests that previous HRP findings, which employed stop distance techniques without simulating robots' autonomy, may also be valid for autonomously approaching robots. Furthermore, as already frequently mentioned throughout this project, the attained frontal mean threshold is greater than most previously gained frontal distances (e.g. Koay et al., 2007; Takayama & Pantofaru, 2009), which may be evoked by a high spatial density of the tested hallway-like environment. Hence, the effect of spatial density on distance preferences, as reported in HHP research (e.g. Hayduk, 1983; Evans & Werner, 2007), seems to apply to HRP as well, which has been also reported in related research (Karreman, Utama, Joosse, Lohse, van Dijk & Evers, 2014). However, some previous studies have also shown similar (Kamide et al., 2014) or even greater frontal approach mean distances (Brandl et al., 2013), but differ in many other study details from the present work (e.g. robots or cultural background). For accepted lateral distances, the existing body of research is very small and no large comparative studies exist to date. Nonetheless, attained findings of the present work align to previous pilot studies (Pacchierotti et al., 2005, 2006) suggesting 0.4m as a comfortable passing distance in a hallway regardless of a robot's autonomy.

Additionally, the present work shows that the assessed mean distances significantly increase due to a faster robot speed (0.8m/s), which has been already observed in previous research (e.g. Brandl et al., 2013). However, the influence of robot speed on subjects' distance preferences is only examined in the first study of this dissertation and therefore it remains open whether a similar effect would occur with autonomously moving robots. Thus, attained insights into accepted frontal and lateral distances are based on a robot speed of 0.6m/s.

Furthermore, findings of the conducted picture rating show significant differences between the transport assistant and Beam regarding their human likeness, animacy and likeability. However, these different robot appearances do not significantly affect subjects' distance preferences except an observed decrease in lateral passing distances by the humanized Beam. It is assumed that this phenomenon occurs due to the projected human eyes on Beam's screen, unconsciously evoking a higher level of trust (and lower induced threat) in the passing maneuver. In contrast, this effect is not observed in frontal scenarios, which is not in accordance with previous research that has reported increases in frontal approach distances by more human-like robots (Butler & Agah, 2001; Koay et al., 2007). It is presumed that the avoidance of mutual gaze between the WoZ and subjects shortly before the stopping of Beam may serve as an explanation. Furthermore, frontal scenarios induce a considerably higher crash risk compared to lateral scenarios, which presumably causes no decrease in frontal distance preferences. In addition, previous human likeness manipulations of Butler and Agah (2001) and Koay et al. (2007) employed stylized, mechanistic-looking, human-like body features to the robots, which may induce more threat to people compared to a real human face.

With respect to the effect in the lateral scenario, this finding highlights the crucial relevance for designers to adapt a robot's appearance to its realistic capabilities in order to avoid misleading expectations and disappointed/frustrated people. The attained result indicates that a projected real human face on Beam's screen significantly affects lateral distance preferences (decrease by more than 0.1m). In contrast, frontal distance findings are valid for all employed robots in the present work, although they are differing in the perceived level of human likeness. Therefore, the present work suggests that positive effects of more human-like robot designs (higher likeability) can be rather safely applied without affecting people's frontal distance preferences to a large extent. Moreover, this finding shows that the accepted frontal mean distance of the present work is presumably greater than many previously gained frontal distances due to the examined dense environment compared to rather open rooms in many previous studies (e.g. Takayama & Pantofaru, 2009), and not caused by employing diverse robots. Accordingly, the present work suggests a high level of generality for the gained accepted frontal mean distances. It can be assumed that these distances are also valid for other robots beyond the transport assistant and Beam. In addition, the present work suggests a higher generality for distance findings of past HRP studies that frequently applied various robots (e.g. Walters et al., 2006; Brandl et al., 2013). Thus, reviewed differences in observed distance preferences presumably occurred due to various other incomparable study details as introduced in section 2.7.3 and its sub-sections. Furthermore, the present work suggests that equipping a robot with human-like eyes could potentially be advantageous for future real-world applications, which have to navigate around humans in highly dense environments, permitting roboticists to program closer passing distances without navigating less acceptably in those environments.

It is further suggested by the present work that the accepted mean distances lack practical relevance due to large individual differences in personal space (Hayduk, 1978). In order to avoid spatial discomfort for a large majority of standing persons in a hallway, the studies show that frontal approach distances of 1.1m and lateral passing distances of 0.6m are more appropriate. Thus, findings suggest that roboticists should rather refer to these values when designing an acceptable first contact with an autonomously moving robot in a hallway. On the other hand, future research needs to examine the influence of people's habituation to robots on their distance preferences. Past research has already observed significant habituation effects (e.g. Koay et al., 2007) that need to be considered in future software frameworks.

In regard to the pursued research question - *Does the distance behavior of an autonomously moving robot affect the overall motion acceptance?* – findings of study II and III show a significant influence. By utilizing the conceptualized questionnaire in study II and III, this question is studied for two diverse mechanoids (transport assistant and Beam). Given the already explored and proven key characteristic of proxemics in human-human (Birdwhistell, 1952; Hall, 1973; Brinker et al., 2000) and human-robot interactions (Walters, 2008), the autonomous frontal and lateral distance management of a robot is expected to impact the overall motion acceptance. In addition, Mori (1970) proclaimed that *'… it is possible to create a safe familiarity with a non-humanlike design'*. Though Mori (1970) has not provided any empirical proof, he has proposed that by designing similar levels of human motion features for a machine-like looking robot, the overall familiarity increases. In addition, several studies in HRI have revealed evidence that robotic motion behavior can lead to positive impressions towards robots (e.g. Kanda et al., 2007). However, to date, it has remained very uncertain whether familiarity or another concept, such as acceptance, might be a more appropriated assessment (Bartneck et al., 2009a; von der Pütten and Krämer, 2012). Since familiarity has been even questioned to be equivalently translatable from Japanese into English (Bartneck et al., 2009a), the present work measured acceptance, which was specified to the prevailing research context, resulting in motion acceptance. Collectively, it is assumed that maintained distances, corresponding to the assessed mean thresholds of comfort positively affect the motion acceptance compared to smaller distances. Additionally, it is hypothesized that greater distances than the accepted mean distances positively affect the motion acceptance as well. As a central result, the assessed ratings of both studies (II and III) primarily show that smaller distances than the mean distances significantly impair the overall motion acceptance of a robot, which supports the first prediction. However, greater maintained distances do not always lead to significantly increased motion acceptance ratings. Furthermore, not all distance variations significantly affect the resulting ratings.

Altogether, these results are generally in line with postulated key meanings of proxemics for human motion behavior, and support a general relevance in human-robot spatial interactions as well. Essentially, the present work validates this effect in relation to two diverse robots, and shows that it is particularly crucial to avoid an overshooting of accepted mean distances. Moreover, this finding aligns to previous research, reporting positive effects of robotic motion behavior on subjects' impressions. The present work suggests that people prefer a robotic motion behavior which considers human spatial conventions (avoiding violations of personal space), which generally aligns to Mori's (1970) assumption (safe familiarity for a non-humanlike design).

The last part of the overall discussion deals with the following central research question: *To what extent obey gained distance findings human spatial conventions?* As already discussed in this chapter, all conducted studies highlight the general relevance of personal space for the present research context. Similar to human-human interactions, proxemics plays an important role for an interaction between a standing human and an autonomously approaching and passing robot in a hallway. As already stated, social robots are embodied and mobile actors in human environments and are aspired to require social capabilities next to functional abilities. In fact, the attained findings show that subjects' desire spatial thresholds of comfort when a robot frontally approaches or laterally passes by them. It is assumed that underlying psychological motives, guiding people's distance preference towards robots, are very similar to the prevailing ones in human-human spatial interaction. Particularly, the *Dosey-Meisels Protection Theory* (Dosey & Meisels, 1969) seems to be very suitable to HRSI contexts as well. This theory also suits the observed phenomenon regarding greater frontal distance preferences compared to lateral ones due to a higher crash risk, which in turn seems to induce a higher level of threat. Thus, mobile social robots in human environments evoke certain levels of threat in humans and these levels of threat in turn guide spatial distance preferences. Similar to HHP, overshooting certain thresholds of comfort causes discomfort. Nonetheless, as shown by the present work and previous studies, these thresholds and their relation to manifold other factors of the robot, the human or the context need to be explored. A simple copying of usual human-human distances is inappropriate.

Given greater frontal mean distances (~0.8m) and even greater practical relevant distances (frontal: 1.1m) than a wide body of reported frontal mean distances in HHP (e.g. 0.51m by Stratton et al., 1973; 0.21m by Horowitz et al., 1964; 0.45m by Ashton & Shaw, 1980), the present work aligns with some previous HRP studies (Brandl et al., 2013; Kamide et al., 2014), and supports the assumption that robots should rather stay farther away from humans compared to other humans (unless during the first contact).

In regard to the proposed notation system by Hall (1966), the present work shows a majority of accepted frontal mean distances within the proposed personal zone (0.46m to 1.2m, Hall, 1966), which is in accordance with most previous HRP research (Hüttenrauch et al., 2006; Kamide et al., 2014). However, as already discussed, it remains questionable whether these zones and corresponding associations either apply to HRP at all, or to a scenario not incorporating any direct interaction. With respect to attained accepted lateral passing distances, a relation to HHP is very complicated. Though the widely postulated egg shape of personal space in HHP (e.g. Ashton & Shaw, 1980; Hayduk, 1981) seems to suit attained findings of the present work, lateral passing distances of the present work are incomparable to the explored lateral approach distances in HHP, which tested direct lateral approaches from the side.

In regard to the perceived human likeness (perceived human likeness of the robot's motion behavior) and *'compare to a human'* ratings (perceived proximity of the robot compared to a usual human behavior in the same situation), attained findings of study II and III demonstrate that humans refer to underlying personal space principles known from human-human interactions, when spatially interacting with a robot. Results show that autonomously maintained distances that correspond to previously assessed mean distances evoke significantly higher ratings of human likeness than smaller maintained distances. It is assumed that less violations of participants' personal space occur around their thresholds of comfort compared to smaller distances, which in turn leads to a more human-like perceived robotic motion behavior. Probably, participants base their assessments on their own underlying social conventions that aim to avoid personal space violations. Therefore, even if the absolute distance is not human-like compared to previous HHP research, the psychological motive to avoid personal space violations is the same. In accordance with these ratings, all *'compare to a human'* assessments support these assumptions. Maintained distances that correspond to the accepted mean distances are rated as most human-like and distances below are rated as way closer compared to a human. Moreover, greater distances than the accepted mean distances are rated as way farther compared to a human. Therefore, designing an adequate proxemic behavior for a robot does not necessarily mean to copy human-human distance values. Instead, it is essential to adapt it to psychological backgrounds and motives that guide daily human-human interactions.

In regard to the captured '*perceived safety around the robot'* and '*expectation conformity of the perceived motion behavior of the robot'*, further support for the previously stated suggestions is obtained. Maintained distances below the accepted mean distances receive a significantly lower perception of safety and also meet participants' expectations significantly less. Accordingly, it can be assumed that a higher number of personal space violations (below the mean distances) are not in consensus with participants' underlying social rules of spatial arrangements within humans. In particular, participants do not expect a personal space violation of a robot and it results in a lower level of the perceived safety. In contrast, it can be presumed that significantly increased safety ratings occur above the mean distances due to less personal space violations. Accordingly, this finding also suits the already proposed *Dosey-Meisels Protection Theory* (Dosey & Meisels, 1969). Thus, attained findings suggest that personal space serves as a mechanism of protection in HRP.

Taken together, the attained findings corroborate central assumptions in HRI (Dautenhahn, 2007, 2013). By investigating a precise motion parameter (proxemics), gained findings support the assumption that it is critical for social robots to possess similar social abilities as humans. However, as it has been shown in previous research (Gockley et al., 2007; Walters, 2008), findings suggest that these abilities should rather consider psychological backgrounds and motives of humans instead of blindly copying human motion properties to robots. To conclude, these findings suggest that participants' actions (study I) and feelings (study II and III) toward the distance behavior of a robot are based on underlying proxemic conventions known from HHI, and in addition, findings show that participants reward a robot's behavior that is designed accordingly. In particular, an autonomously moving robot in a hallway that considers humans' underlying spatial norm of avoiding violations of personal space, independent from whether the demanded distances are greater between humans and robots than between humans, poses a social skill which leads to significantly less numbers of disaffected people.

Nonetheless, it is crucial to consider a high internal validity of the conducted laboratory experiments and to address derived assumptions in future research, which is more precisely discussed in the following section.

7 Limitations and Future Research

At first, as already mentioned in the end of the preceding section, all attained findings, corresponding interpretations and derived relevances are up to this point only valid within the confines of this doctoral project. In particular, the obtained findings and corresponding interpretations are true for the examined research context, encompassing two diversely looking robots autonomously approaching or passing one standing person in a 2.9m wide hallway-like environment. Additionally, several other details of the experimental samples, settings, materials, tasks, designs and procedures regularize the generality of the findings. In favor of increasing the generality and external validity of attained results, further lab and field studies, replicating and advancing the current body of knowledge, are required. The central limitations of the present research project are subsequently analyzed and corresponding suggestions for future research are represented in the succeeding paragraphs.

First, though the present work poses a systemically conceptualized approach to advance prevailing drawbacks in HRSI by internally validating attained results for diverse robots, the utilized platforms had not been used in previous HRSI research before, which complicates a comparison. Unfortunately, this doctoral research project is limited by the available robotic systems at Bosch and the internally developed robotic prototype (transport assistant) will not be purchasable for other researchers. However, at least Beam is a commercially available robot and future researchers should feel encouraged to employ it in order to design comparable studies. Although the conducted work of this dissertation suggests only a significant influence of a robot's outward design on subjects' lateral distance preferences, future studies are required in order to validate the attained findings and derived assumptions for other robots. In addition, future work should investigate attained effects by diversely humanizing a robot, for instance, adding stylized human-like eyes to a robot. In general, the interplay of robot appearance features (e.g. size, human likeness) and motion behavior should be more thoroughly investigated in the future.

Second, attained findings of this dissertation exclusively provide an empirical framework for a relatively static setting, exploring preferences of a standing person in a hallway. Thus, consecutive studies should investigate more dynamic scenarios, such as a moving person in a hallway, a direct interaction scenario with a robot, or a complete avoidance maneuver of a robot. In a pilot study run by Pacchierotti et al. (2005), initial results have been already obtained for the latter, indicating that participants were most comfortable with a robot speed of 0.6m/s, a signal distance of 6.0m and a lateral passing distance of 0.4m. In addition, the present work gained internally valid findings for one person. Accordingly, desired distance preferences for a pair of people or a group of multiple people should be subject of investigation in future research as well. Related work has already shown that a higher level of social as well as spatial density significantly affects a comfortable HRSI (Karreman et al., 2014). Moreover, it needs to be mentioned that reported findings are only valid for the examined hallway-like dimensions. Presumably, narrower hallways or environments (e.g. elevator) lead to an increase in accepted mean distances. Additionally, attained distance findings may not be valid for larger open areas. Accordingly, the present work exclusively provides an empirical starting base for future investigations addressing diverse environments. In line with the confines of the examined environment, it remains questionable whether greater distances than 1.1m (frontal) and 0.6m (lateral) may lead to even higher majorities of comfortable participants. Succeeding studies should therefore also explore greater maintained distances. Furthermore, in regard to all conducted distance measurements, it is relevant to consider that participants were informed about the scope of all studies, which has been suggested to slightly decrease the size of personal space by 8% compared to unobtrusive measurements (Hayduk, 1978). Thus, the validity of attained distances should be verified by using unobtrusive methods in the field.

Third, the precise relevance of a robot's proxemic behavior for the overall motion acceptance cannot be exactly scrutinized. Though attained findings indicate a crucial relevance for avoiding smaller distances than accepted mean distances, further motion attributes of a robot and their potential interplay with proxemics as well as their potential effects on motion acceptance should be researched in the future. Appropriate robot speed has been already postulated to improve the overall acceptance (Brandl et al., 2013) and should therefore be seen as a further key feature of an acceptable robotic motion behavior. Whether even smaller speed differences (e.g. 0.1m/s) or different speed values (e.g. 1m/s) than the tested in the present work significantly influence people's distance preferences remains to be validated in future work. Furthermore, the employed robots in the present work show rather high acceleration values, resulting in a rather abrupt starting and stopping. Presumably, a robot's level of acceleration could pose a further relevant variable for a robot's motion acceptance.

Fourth, a further limitation of the conducted work is posed by the missing exploration of participants' increasing level of habituation (upon a second exposure) over time and its effect on distance preferences. Moreover, subjects of the present work rather had no general prior experience with robots and no high robot familiarity with the employed systems. However, since most societies are not used to social robots, designing an acceptable first human-robot contact is of high relevance (Bartneck et al., 2009b). Thus, obtained findings are crucial for the current state regarding a societal integration of robots. Furthermore, many robotic real-world applications exclusively involve short-term encounters, such as a delivery robot (Koay et al., 2007). However, by progressively encountering more robots in daily life, or the same robot multiple times a day, parameter settings, which are adapted to first encounters, may start to annoy people (Koay et al., 2007). Though in the first study this highly relevant factor is initially considered, study II and III do not address this issue anymore due to fatigue and motivational constraints of participants.

Undoubtedly, the level of familiarity, as in many other fields of human-machine interaction, plays a vital role in shaping humans' attitudes, expectation, acceptance and behavior. Furthermore, reviewed literature has already accentuated this for human-human (Hall, 1966; Argyle, 1975; Sommer, 2002a) and human-robot proxemics as well (Koay et al., 2007; Takayama & Pantofaru, 2009; Walters et al., 2011). Therefore, future studies should explore the validity of attained distance findings for an increased robot familiarity. Since it is impossible to capture a person's degree of robot familiarity by a sensor, gathering certain familiarity patterns of diverse target populations would be helpful for adapting the robotic behavior to a specific environment. According to a gradually emergence of robotic technology into human environments, this subject will be most likely of high relevance in the future.

Moreover, in relation to postulated influences of people's level of familiarity among each other and corresponding personal space zones (Hall, 1966), conducted experiments cannot clarify whether these zones apply at all to people's level of familiarity with robots, or to indirect interaction scenarios between humans and robots. Thus, future research should examine this subject by assessing participants' perceived relation to robots and potential changes over time.

In addition, attained findings are based on people who are relatively young and belong to non-contact cultures. Hence, in favor of carrying results over to older age groups and contact cultures, future work should address this subject as well. Particularly, future studies that aim to validate gained findings for older people should be of high relevance for robotic companies since nursing homes already pose an established market with a high growth potential.

Lastly, the newly proposed working standard, regarding a distance adjustment based on the participants' belly/hip region, is seen as beneficial in many aspects. However, it simultaneously requires a laser scanner installation at an appropriate height, which in turn may limit the height flexibility and/or outward design of a future social robot. In particular, this requirement could be detrimental for future domestic robot designs that intend to appear cute by being rather small. In addition, the pursued methodological approach cannot examine personal space areas behind a person, which are of high practical relevance for a *'follow me scenario'*. Furthermore, this work does not provide insights into accepted lateral approach distances when a robot approaches a person directly from the side. Therefore, future lab experiments should expand the current body of knowledge by addressing this subject.

8 Overall Conclusion

The primary research goal of this dissertation is to systematically explore accepted frontal approach and lateral passing distances of an autonomously moving robot toward a standing human in a hallway. Supplementary, this work examines potential dependencies of human distance preferences to a robot's level of speed and human likeness. In addition, this work investigates the relevance of a robot's proxemic behavior for the overall motion acceptance, and gains further insights into prevailing psychological motives guiding people's preferences in a HRSI in a hallway. Towards these central goals, the present research project provides pivotal insights, which are recapped in the consecutive passage.

At first, the conducted research unveils that frontal approach and lateral passing distance preferences toward an autonomously moving robot in a hallway exist, and that these preferences are of vital relevance for avoiding feelings of discomfort and for increasing subjects' perceived safety, expectation conformity and overall motion acceptance toward a robot. Within the confines of the examined research context, an accepted frontal approach mean distance of approximately 0.8m and an accepted lateral passing mean distance of approximately 0.4m are assessed. Primarily, the conducted research shows that these distances are not significantly influenced by a robot's simulated autonomy. In contrast, the conducted examination indicates that a faster robot speed of 0.8m/s than 0.6m/s significantly increases subjects' distance preferences. By considering this finding, it is crucial to mention that the accepted mean distances are exclusively valid for a robot speed of 0.6m/s. In addition, the present investigation exclusively indicates significant influences of a more human-like looking Beam on subjects' lateral distance preferences (decrease by more than 0.1m in the accepted lateral mean distance when human eyes are displayed on Beam's screen). Accordingly, the gained spatial thresholds of comfort can be assumed to hold true for different robots autonomously approaching or passing a standing human in a hallway. However, this work suggests that human-like design features of robots (e.g. size, height) can lead to higher levels of human-likeness, animacy, and likeability, which might pose a relevant implication for the design of future real-world applications. Furthermore, by considering a desired large majority of comfortable individuals during a first encounter with a robot, accepted frontal approach distances of 1.1m and accepted lateral passing distances of 0.6m are suggested.

In addition, the present work provides insights into participants' psychological motives guiding their preferences for an acceptable HRSI in a hallway. Attained results suggest that humans' underlying understanding of spatial conventions, known from HHI, guide their expectations and feelings towards social service robots as well. Presumably, subjects see a mobile social service robot as a threat they can potentially collide with, which in turn induces a need for protection toward an approaching or passing robot which determines the desired distances toward this robot. By invading people's personal space, feelings of discomfort arise, which in turn leads to a significantly decreased motion acceptance of the robot. Thus, it is of crucial relevance to explore and design a socially appropriate proxemic behavior in order to avoid disaffected people the robot shares the environment with. Nonetheless, it remains uncertain to what extent the overall motion acceptance of a robot is influenced by other robotic motion characteristics, such as speed or acceleration. Taken together, it can be concluded that an adequate frontal approach and lateral passing distance management poses a critical requirement for a social service robot in a hallway, since overshooting accepted mean distances causes disaffected people.

Beyond these findings, the pursued experimental method poses the first systematic exploration of a socially appropriate robotic distance behavior in a hallway to date. By considering the biometrics of a human, a new working standard in HRP research is introduced. In addition, the conceptualized method permits an inter-study comparison and thus, initially pursues to shed light on the potential effects of diverse robots on people's distance preferences. Accordingly, the conception of the present work contributes to a higher generality of attained findings.

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Appendix A

GODSPEED questionnaires (Bartneck, C., Kulić, D., Croft, E., & Zoghbi, S. (2009)

GODSPEED I: ANTHROPOMORPHISM

Please rate your impression of the robot on these scales:

以下のスケールに基づいてこのロボットの印象を評価してください。

Fake 偽物のような	1	2	3	4	5	Natural 自然な
Machinelike 機械的	1	2	3	4	5	Humanlike 人間的
Unconscious 意識を持たない	1	2	3	4	5	Conscious 意識を持っている
Artificial 人工的	1	2	3	4	5	Lifelike 生物的
Moving rigidly ぎこちない動き	1	2	3	4	5	Moving elegantly洗練された動き

GODSPEED II: ANIMACY

Please rate your impression of the robot on these scales:

以下のスケールに基づいてこのロボットの印象を評価してください。

Dead 死んでいる	1	2	3	4	5	Alive 生きている
Stagnant 活気のない	1	2	3	4	5	Lively 生き生きとした
Mechanical 機械的な	1	2	3	4	5	Organic 有機的な
Artificial 人工的な	1	2	3	4	5	Lifelike 生物的な
Inert 不活発な	1	2	3	4	5	Interactive 対話的な
Apathetic 無関心な	1	2	3	4	5	Responsive 反応のある

GODSPEED III: LIKEABILITY

Please rate your impression of the robot on these scales:

以下のスケールに基づいてこのロボットの印象を評価してください。

Dislike 嫌い	1	2	3	4	5	Like 好き
Unfriendly 親しみにくい	1	2	3	4	5	Friendly 親しみやすい
Unkind 不親切な	1	2	3	4	5	Kind 親切な
Unpleasant 不愉快な	1	2	3	4	5	Pleasant 愉快な
Awful ひどい	1	2	3	4	5	Nice 良い

GODSPEED IV: PERCEIVED INTELLIGENCE

Please rate your impression of the robot on these scales:

以下のスケールに基づいてこのロボットの印象を評価してください。

Incompetent 無能な	1	2	3	4	5	Competent 有能な
Ignorant 無知な	1	2	3	4	5	Knowledgeable 物知りな
Irresponsible 無責任な	1	2	3	4	5	Responsible 責任のある
Unintelligent 知的でない,	1	2	3	4	5	Intelligent 知的な
Foolish 愚かな	1	2	3	4	5	Sensible 賢明な

GODSPEED V: PERCEIVED SAFETY

Please rate your emotional state on these scales:

以下のスケールに基づいてあなたの心の状態を評価してください。

Anxious 不安な	1	2	3	4	5	Relaxed 落ち着いた
Agitated 動揺している	1	2	3	4	5	Calm 冷静な
Quiescent 平穏な	1	2	3	4	5	Surprised 驚いた

Appendix B

Computed repeated measures 3-way ANOVAs for examining the influence of gender on each block of the first study (frontal and lateral distance)

Independent Variable	Effect	F (df1,df2)	p	η^2
Speed (S)	**frontal distance**	**(1,34) = 4.754**	**0.036**	**0.126**
	lateral distance	**(1,34) = 6.896**	**0.013**	**0.173**
Type of contact (TC)	frontal distance	(1,34) = 0.372	0.546	0.011
	lateral distance	(1,34) = 1.724	0.198	0.050
Gender (G)	**frontal distance**	**(1,34) = 7.006**	**0.012**	**0.175**
	lateral distance	(1,34) = 0.340	0.564	0.010
S x TC	frontal distance	(1,34) = 2.653	0.113	0.074
	lateral distance	(1,34) = 0.137	0.714	0.004
G x S	frontal distance	(1,34) = 0.024	0.877	0.01
	lateral distance	(1,34) = 0.296	0.590	0.009
G x TC	frontal distance	(1,34) = 1.085	0.305	0.032
	lateral distance	(1,34) = 0.026	0.873	0.001
G x S x TC	frontal distance	(1,34) = 0.152	0.699	0.005
	lateral distance	(1,34) = 0.371	0.547	0.011

Note: significant effects are printed in bold

Appendix C

Sample comparisons

Sample Variable	Study I	Study II		
	Mean	**Mean**	**t(73)**	**p**
Age	33,69	29,2	2,438	0,017
Gender	51,4% female/48,6% male	50% female/male	-0,122	0.903
Cultural background	94% Germans	95% Germans	0,136	0,893
Professional background	68,6% non-technical	67,5% non-technical	0,119	0,905
Prior experience with autonomous systems	85,7% None	77,5% None	-0,956	0,342
Prior experience with applied robot	67,5% none	75% none	1,548	0,126

Sample Variable	Study II	Study III		
	Mean	**Mean**	**t(78)**	**p**
Age	29,2	35,2	-2,940	0.004
Gender	50% female/male	55% female/45%male	0,443	0.659
Cultural background	95% Germans	32,5% Germans	-7,555	0,000
Professional background	67,5% non-technical	47,5% non-technical	1,400	0,165
Prior experience with autonomous systems	77,5% None	90% none	-2,561	0,012
Prior experience with applied robot	75% none	60% none	-1,461	0,148

Appendix D

Instruction sheet of study II

Befragung zum Bewegungsverhalten eines autonomen Assistenten

Instruktion

Sehr geehrte(r) Versuchsteilnehmer(-in),

im Folgenden nehmen Sie an einem Versuch teil in dem es um einen autonomen Assistenten von Bosch geht.

Ziel dieser Befragung ist es, Ihre Meinung zu dem Bewegungsverhalten des autonomen Assistenten zu erfahren, den Sie in 10 Durchgängen kennenlernen werden. Um Ihnen zu Beginn ein besseres Verständnis über den autonomen Assistenten zu ermöglichen, folgt eine kurze Beschreibung dazu:

Bosch hat einen „autonomen Transportassistenten" für Krankenhäuser entwickelt, eine Art selbständig fahrende Plattform, die dem Krankenhauspersonal Transportaufgaben abnimmt. Dabei soll der Transportassistent das vorhandene Personal nicht ersetzen, sondern unterstützen. Häufig hat das Krankenhauspersonal keine Zeit neben Ihren Hauptaufgaben verschiedenste Nebentätigkeiten wie Transporte zu übernehmen. Der Transportassistent fährt selbstständig auf zuvor „gelernten" Fluren/Gängen (auch in Aufzügen) und transportiert im Krankenhaus zum Beispiel Medikamente, Hilfsmittel und Wäsche. Autonom fahren bedeutet, dass sowohl das Krankenhauspersonal als auch Besucher des Krankenhauses oder Patienten diesem „Transportassistenten" alleine begegnen können.

Sollten Sie weitere Fragen zum Assistenten haben, stellen Sie diese bitte gerne im Anschluss des Versuchs. Der Versuch wird maximal 60 Minuten dauern.

In den anschließenden 10 Teilversuchen bitten wir Sie sich immer auf die markierten Positionen zu stellen und dann den weiteren Anweisungen des Versuchsleiters zu folgen. **Stellen Sie sich vor, dass Sie in einem Gang stehen. Der autonome Assistent wird entweder vor Ihnen anhalten oder an Ihnen vorbeifahren.** Im Anschluss an jeden Durchgang werden Sie einen Fragebogen zu dem davor erlebten Bewegungsverhalten des autonomen Assistenten bekommen und diesen dann bitte bearbeiten. Unter dem

Bewegungsverhalten werden der eingehaltene seitliche und frontale Abstand des autonomen Assistenten verstanden. **Dabei gibt es keine falschen oder richtigen Antworten, es interessieren uns ausschließlich Ihre spontanen Eindrücke nach Ihrem eigenen freien Ermessen!**

Sie müssen keine Bedenken hinsichtlich Ihrer Gesundheit haben, da der Versuchsleiter in das Verhalten des autonomen Assistenten jederzeit eingreifen kann.

Sie werden nun gleich dem autonomen Assistenten begegnen. Folgen Sie stets den Anweisungen des Versuchsleiters. Sollten Sie Fragen oder Probleme haben, können bzw. sollten Sie diese umgehend dem Versuchsleiter mitteilen.

Vielen Dank für Ihre Teilnahme!

Appendix E

Questionnaire upon frontal trials in study II

Zwischenbefragung zum Bewegungsverhalten eines autonomen Assistenten

Bitte beantworten Sie die folgenden Fragen spontan und machen sie dafür in jeder Zeile ein Kreuz (☒). Es gibt keine richtigen oder falschen Antworten.

Fragen zur eben erlebten Situation

	Stimme nicht zu	Stimme eher nicht zu	Neutral	Stimme eher zu	Stimme außerordentlich zu
Das Bewegungsverhalten war autonomen Assistenten ist gut.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten löste in mir ein unwohles Gefühl aus.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war vorhersehbar.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war überraschend.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war befremdlich.	❒	❒	❒	❒	❒
Einem autonomen Assistenten mit einem solchen Abstandsverhalten würde ich vertrauen.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war höflich.	❒	❒	❒	❒	❒
Der autonome Assistent hat sich so verhalten wie ich es erwartet habe.	❒	❒	❒	❒	❒

	Gar nicht	Kaum	Neutral	Etwas	Sehr
Empfanden Sie den eingehaltenen Abstand vom autonomen Assistenten zu Ihnen als unangenehm?	❒	❒	❒	❒	❒
Wie sicher haben Sie sich in der Nähe des autonomen Assistenten gefühlt?	❒	❒	❒	❒	❒
Wie menschenähnlich hat sich der autonome Assistent verhalten?	❒	❒	❒	❒	❒

Wie empfanden Sie den Abstand, den der autonome Assistent beim Heranfahren zu Ihnen gewählt hat?	viel zu nah		etwas zu nah		nicht zu nah
	❒	❒	❒	❒	❒

Im Vergleich zu einem sich in dieser Situation üblicherweise verhaltenen Menschen, fuhr der autonome Assistent:	Näher heran	Etwas näher heran	Ähnlich nah heran	etwas weiter weg heran	weiter weg heran
	❒	❒	❒	❒	❒

Questionnaire upon lateral trials in study II

Zwischenbefragung zum Bewegungsverhalten eines autonomen Assistenten

Bitte beantworten Sie die folgenden Fragen spontan und machen sie dafür in jeder Zeile ein Kreuz (☒). Es gibt keine richtigen oder falschen Antworten.

Fragen zur eben erlebten Situation

	Stimme nicht zu	Stimme eher nicht zu	Neutral	Stimme eher zu	Stimme außerordentlich zu
Das Bewegungsverhalten des autonomen Assistenten war gut.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten löste in mir ein unwohles Gefühl aus.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war vorhersehbar.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war überraschend.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war befremdlich.	❒	❒	❒	❒	❒
Einem autonomen Assistenten mit einem solchen Abstandsverhalten würde ich vertrauen.	❒	❒	❒	❒	❒
Das Bewegungsverhalten des autonomen Assistenten war höflich.	❒	❒	❒	❒	❒
Der autonome Assistent hat sich so verhalten wie ich es erwartet habe.	❒	❒	❒	❒	❒

	Gar nicht	Kaum	Neutral	Etwas	Sehr
Empfanden Sie den eingehaltenen Abstand vom autonomen Assistenten zu Ihnen als unangenehm?	❐	❐	❐	❐	❐
Wie sicher haben Sie sich in der Nähe des autonomen Assistenten gefühlt?	❐	❐	❐	❐	❐
Wie menschenähnlich hat sich der autonome Assistent verhalten?	❐	❐	❐	❐	❐

Wie empfanden Sie den Abstand, den der autonome Assistent beim Vorbeifahren zu Ihnen gewählt hat?	viel zu nah		etwas zu nah		nicht zu nah
	❐	❐	❐	❐	❐

Im Vergleich zu einem sich in dieser Situation üblicherweise verhaltenen Menschen, fuhr der autonome Assistent:	Näher vorbei	Etwas näher vorbei	Ähnlich nah vorbei	Etwas weiter weg vorbei	Weiter weg vorbei
	❐	❐	❐	❐	❐

Appendix F

Instruction sheet of study III

Evaluation of BEAM's motion behavior

Instruction

Dear participant,

You are being asked to take part in a research study on BEAM's motion behavior. The study's goal is to gather your personal assessment of diverse types of BEAM's motion behavior. As a result, you will experience a variation of 10 different trials followed by a short questionnaire after each condition.

In order to provide you with a better understanding of BEAM and its functions please read the following brief introduction.

Mobile telepresence systems are characterized by a video conferencing system mounted on a mobile base. BEAM has video and audio quality comparable to professional video conference systems and autonomously drives around. The interaction involves talking with and seeing a user on the robot's screen.

There are no further details provided to you at this point of the study on purpose. If you have additional questions please feel free to ask them at the end of the study. The whole procedure lasts at most 60min.

In the course of the upcoming 10 trials we ask you to always position yourself on the marked places on the floor and then follow further instructions given to you by the examiner. **Please try to imagine that you are in a hallway. BEAM will either autonomously stop in front of you or autonomously pass right next to you.** After each trial you will receive a short questionnaire assessing your subjective impressions of the experienced motion behavior. **With respect to the motion behavior, the study refers to the maintained frontal as well as lateral distances of BEAM towards you. However, there are no correct or incorrect answers – we are only interested in your individual and spontaneous impressions after each trial.** There are no known risks regarding your participation in this research study. The examiner can intervene during the autonomous behavior of BEAM at any time.

If you have any questions or concerns please do not hesitate to ask the examiner.

Thank you very much for your participation!

Appendix G

Questionnaires for the picture rating

What do you think about the autonomous assistant presented in the picture? Please mark your choice spontaneously with a cross (☒). There are no correct or incorrect answers.

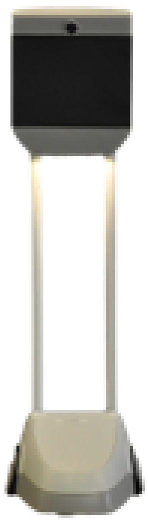
fake	❐	❐	❐	❐	❐	natural
machine-like	❐	❐	❐	❐	❐	human-like
unconscious	❐	❐	❐	❐	❐	conscious
artificial	❐	❐	❐	❐	❐	lifelike
dislike	❐	❐	❐	❐	❐	like
unfriendly	❐	❐	❐	❐	❐	friendly
unkind	❐	❐	❐	❐	❐	kind
unpleasant	❐	❐	❐	❐	❐	pleasant
awful	❐	❐	❐	❐	❐	nice
dead	❐	❐	❐	❐	❐	alive
stagnant	❐	❐	❐	❐	❐	lively
mechanical	❐	❐	❐	❐	❐	organic

inert	❒	❒	❒	❒	❒	interactive
apathetic	❒	❒	❒	❒	❒	responsive

	strongly disagree	slightly disagree	neutral	Slightly agree	strongly agree
The autonomous assistant somehow appears familiar to me.	❒	❒	❒	❒	❒
The autonomous assistant somehow appears uncanny to me.	❒	❒	❒	❒	❒

Evaluation of BEAM

What do you think about the autonomous assistant presented in the picture? Please mark your choice spontaneously with a cross (☒). There are no correct or incorrect answers.



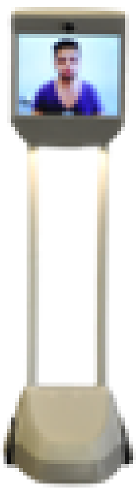
fake	❒	❒	❒	❒	❒	natural
machine-like	❒	❒	❒	❒	❒	human-like
unconscious	❒	❒	❒	❒	❒	conscious
artificial	❒	❒	❒	❒	❒	lifelike
dislike	❒	❒	❒	❒	❒	like

unfriendly	❒	❒	❒	❒	❒	friendly
unkind	❒	❒	❒	❒	❒	kind
unpleasant	❒	❒	❒	❒	❒	pleasant
awful	❒	❒	❒	❒	❒	nice
dead	❒	❒	❒	❒	❒	alive
stagnant	❒	❒	❒	❒	❒	lively
mechanical	❒	❒	❒	❒	❒	organic
inert	❒	❒	❒	❒	❒	interactive
apathetic	❒	❒	❒	❒	❒	responsive

	strongly disagree	slightly disagree	neutral	Slightly agree	strongly agree
The BEAM somehow appears familiar to me.	❒	❒	❒	❒	❒
The BEAM somehow appears uncanny to me.	❒	❒	❒	❒	❒

Evaluation of BEAM

What do you think about the autonomous assistant presented in the picture? Please mark your choice spontaneously with a cross (☒). There are no correct or incorrect answers.



fake	❒	❒	❒	❒	❒	natural
machine-like	❒	❒	❒	❒	❒	human-like
unconscious	❒	❒	❒	❒	❒	conscious
artificial	❒	❒	❒	❒	❒	lifelike
dislike	❒	❒	❒	❒	❒	like
unfriendly	❒	❒	❒	❒	❒	friendly
unkind	❒	❒	❒	❒	❒	kind
unpleasant	❒	❒	❒	❒	❒	pleasant
awful	❒	❒	❒	❒	❒	nice
dead	❒	❒	❒	❒	❒	alive
stagnant	❒	❒	❒	❒	❒	lively
mechanical	❒	❒	❒	❒	❒	organic
inert	❒	❒	❒	❒	❒	interactive
apathetic	❒	❒	❒	❒	❒	responsive

	strongly disagree	slightly disagree	neutral	Slightly agree	strongly agree
The BEAM somehow appears familiar to me.	❒	❒	❒	❒	❒
The BEAM somehow appears uncanny to me.	❒	❒	❒	❒	❒

Appendix H

Questionnaire upon lateral trials in study III

Evaluation of the BEAM’s motion behavior

Please respond spontaneously to the questions and mark your choice with a cross (☒). There are no correct or incorrect answers.

Questions regarding the experienced trial:

	strongly disagree	slightly disagree	neutral	slightly agree	strongly agree
The BEAM’s motion behavior was good.	❒	❒	❒	❒	❒
The BEAM’s motion behavior made me feel uncomfortable.	❒	❒	❒	❒	❒
The BEAM’s motion behavior was predictable.	❒	❒	❒	❒	❒
The BEAM’s motion behavior was surprising.	❒	❒	❒	❒	❒
The BEAM’s motion behavior was strange.	❒	❒	❒	❒	❒
I would trust in a BEAM with such kind of distance behavior.	❒	❒	❒	❒	❒
The BEAM’s motion behavior was polite.	❒	❒	❒	❒	❒
The BEAM’s motion behavior was exactly like I expected it.	❒	❒	❒	❒	❒

	not at all	barely	neutral	a bit	very

Did the chosen distance from the BEAM make you feel uncomfortable?	❒	❒	❒	❒	❒
How safe did you feel around the BEAM?	❒	❒	❒	❒	❒
How human-like was the BEAM's behavior?	❒	❒	❒	❒	❒

How would you rate the BEAM's maintained lateral distance towards you?	way too close		a bit too close		not too close at all
	❒	❒	❒	❒	❒

Compared to a human in the same situation, the BEAM passed me:	way closer	barely closer	similar to a human	a bit farther	way farther
	❒	❒	❒	❒	❒

Questionnaire upon frontal trials in study III

Evaluation of the BEAM's motion behavior

Please respond spontaneously to the questions and mark your choice with a cross (☒). There are no correct or incorrect answers.

Questions regarding the experienced trial:

	strongly disagree	slightly disagree	neutral	slightly agree	strongly agree
The BEAM's motion behavior was good.	❒	❒	❒	❒	❒
The BEAM's motion behavior made me feel uncomfortable.	❒	❒	❒	❒	❒
The BEAM's motion behavior was predictable.	❒	❒	❒	❒	❒

The BEAM's motion behavior was surprising.	❒	❒	❒	❒	❒
The BEAM's motion behavior was strange.	❒	❒	❒	❒	❒
I would trust in a BEAM with such kind of motion behavior.	❒	❒	❒	❒	❒
The BEAM's motion behavior was polite.	❒	❒	❒	❒	❒
The BEAM's motion behavior was exactly like I expected it.	❒	❒	❒	❒	❒

	not at all	barely	neutral	a bit	very
Did the chosen distance from the BEAM make you feel uncomfortable?	❒	❒	❒	❒	❒
How safe did you feel around the BEAM?	❒	❒	❒	❒	❒
How human-like was the BEAM's motion behavior?	❒	❒	❒	❒	❒

How would you rate the BEAM's maintained frontal distance towards you?	way too close		a bit too close		not too close at all
	❒	❒	❒	❒	❒

Compared to a human in the same situation, the BEAM approached me:	way closer	barely closer	similar to a human	a bit farther	way farther
	❒	❒	❒	❒	❒

Appendix I

Befragung zum Bewegungsverhalten eines autonomen Assistenten

Vorbefragung

Fragen zu Ihrer Person – Bitte machen Sie im Folgenden Angaben zu Ihrer Person

Wie alt sind Sie? _____ Jahre

Sie sind:	❒ weiblich	❒ männlich		
Welcher Nationalität gehören Sie an? ________________________________				
Falls Sie berufstätig sind: Ist Ihre aktuelle Tätigkeit eher überwiegend technisch oder nicht-technisch?				
❒ technisch	❒ nicht-technisch	❒ weder noch		
Haben Sie beruflich oder privat mit dem Thema autonome Systeme zu tun? (z.B. automatischer Rasenmäher/Staubsauger)				
❒ nein	❒ ja, selten	❒ ja, manchmal	❒ ja, oft	❒ ja, sehr oft
	Mit dem Thema: ________________________			
Haben Sie diesen autonomen Assistenten bereits gesehen?				
❒ nein	❒ ja, live	❒ ja, auf Bildern bzw. in Videos		

Appendix J

Evaluation of the BEAM

Preliminary Interview

Demographic Section

How old are you? ______ years

What is your gender?	❒ female ❒ male
What is your nationality? ________________	
Which country did you grow up in? ________________	
If you are currently employed: is your current work position more technical (e.g. engineering) or non-technical (e.g. marketing), or neither? ❒ technical ❒ non-technical ❒ none of both	
Have you ever interacted with robotic systems, either for work or in your private life? (e.g. autonomous lawn mower / robotic vacuum cleaner)	
❒ no	❒ barely ❒ sometimes ❒ often ❒ very often
Have you ever seen the BEAM before? ❒ no ❒ yes in person ❒ yes, but only on pictures or videos	