Spatial Coordination

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Human and Robotic Communicative Whole-Body Motions in Narrow Passages

Annika Peters

Abdruck der genehmigten Dissertation *“Spatial Coordination - Human and Robotic Communicative Whole-Body Motions in Narrow Passages”*
zur Erlangung des akademischen Grades Doktor-Ingenieur (Dr.-Ing.)
der Technischen Fakultät der Universität Bielefeld
am 29.08.2012 vorgelegt von Annika Peters
am 20.11.2012 verteidigt und genehmigt.

Gutachter:
apl. Prof. Dr.-Ing. Franz Kummert, Universität Bielefeld
Prof. Dr. Thomas Schack, Universität Bielefeld
Dr.-Ing. Marc Hanheide, University of Lincoln

Prüfungsausschuss:
Prof. Dr.-Ing. Barbara Hammer, Universität Bielefeld
apl. Prof. Dr.-Ing. Franz Kummert, Universität Bielefeld
Prof. Dr. Thomas Schack, Universität Bielefeld
Dr.-Ing. Marc Hanheide, University of Lincoln
Dr.-Ing. Thorsten Jungeblut, Universität Bielefeld

Gedruckt auf alterungsbeständigem Papier nach ISO 9706

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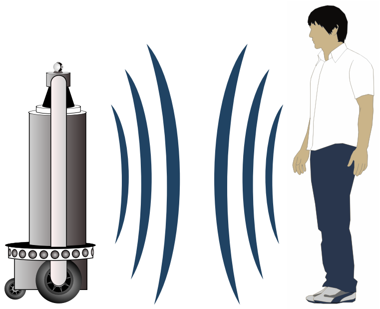

A dissertation submitted to Bielefeld University
in partial fulfilment of the requirements for the degree of

Doktor-Ingenieur
(Dr.-Ing.)

August 2012

Universität Bielefeld
Angewandte Informatik
Technische Fakultät
Universitätsstr. 25
33615 Bielefeld
Germany

Acknowledgements

I think my PhD thesis would have not been possible without the support of my colleagues, friends, and family. These groups of people supported me morally and via scientific discussions. Therefore, I would like to thank you for your support during the entire time of being a PhD student and through ups and downs of the normal life of a PhD. Thank you – for your support and distraction to keep me sane.

I would like to thank, in particular, Sascha Griffiths, for many hours of fruitful discussions and support whenever I needed someone to tell me that my thesis is great. I would like to thank these really nice people for their stamina, reliability and their helpful and motivating comments while reading parts of my thesis: Sascha, John, Thorsten, Petra, Seana, Lhinn, Pete, Jessy and my Hobman Family. I like to thank the student assistants Sascha, Jens, Jenny, and Natalie for their stamina in coding my video data.

I also would like to thank my supervisors Marc Hanheide and Franz Kummert for their support over the last three years whenever I needed it. Thanks Marc, for many Skype calls and helpful comments. I also would like to thank Petra Weiss and Thorsten Spexard for guiding me through first year of my PhD. Moreover, I would like to mention Thomas Schack, who supported me right away whenever I asked him to. Thanks for reading my thesis.

I owe special thanks to Bastian Kriesten, who supported me all along the way – through ups and downs and tried to keep me sane, which I have to admit hasn't been easy – sometimes. Thank you.

Abstract

The focus of this thesis is the nonverbal communication via robotic and human whole-body motions in HRI. Humans have the natural ability to nonverbally communicate with each other via whole-body motion and are very able to interpret and predict motions of others, e.g., in order to coordinate themselves with others in narrow environments. This thesis investigates the communicative potential of whole-body motions not only on the robotic side of conveying motion but also on the human side in HRI. To observe human interpretation of robot motion and to observe human communicative whole-body motion in interaction, two studies have been conducted. A result of the studies is that abrupt motions and motions which are bounded with pauses are clearer to interpret. A human interprets robotic motions as reaction to her / his own presence if the robotic motion is abrupt, e.g., humans attribute intentional behaviour more to a driving robot, which stops or to a robot which has not been moving and then moves compared to a robot which has been moving constantly. Another important result of the studies is the creation of a coding scheme based on a detailed description of human whole-body motions and their associated characteristics. Small steps are conveyed and bounded with pauses. Characteristics of motion (trajectory, distance, position, orientation) are analysed as to whether they form any patterns that represent specific communicative whole-body motions. This thesis discusses that a mere representations of two moving objects is not enough for a robot to interpret communicative whole-body motions. A relative and qualitative framework of representing motions and its advancements are used and discussed. This thesis identifies the need for a system to represent possible interpretations or meanings according to the observed communicative motions for robots. This PhD thesis is a fundamental and interdisciplinary work and the basis for different future projects which have been already initiated. This thesis provides pieces of advice of how a robot should cope with the communicative power of whole-body motions in HRI. A robot should: *a) consider human communicative whole-body motion and ask for its meaning. b) be aware of the own motion. c) express goal-directed actions.*

Contents (short)

Contents

Chapter 1

Introduction

There are mobile service robots, which are especially designed for human-robot interaction (HRI). These mobile robots can currently be found, for example, in museums [Clodic et al., 2006], in do-it-yourself stores [Ludewig et al., 2011; Poeschl et al., 2011] and at the Hanover Trade Fair[1]. Soon these robots will be able to assist in all kinds of home situations, as well as in offices and shops. They will not only have to cope with different interiors, but also with a variety of different tasks and humans and, as these humans cannot be expected to be expert in the robot's technical processes in order to use it, the interpretation of human nonverbal behaviour becomes essential [Pacchierotti et al., 2006]. Furthermore, there are situations which pose particular challenges, e.g., where the robot is blocking the path for a human or vice versa. Humans usually solve these problems nonverbally, especially when interaction partners are able to move [Frith and Frith, 2006]. An additional consideration is that it is important that humans should be comfortable with robot behaviour [Walters et al., 2005a]. A key factor therein is being able to predict an interaction partner's next action [Butler and Agah, 2001]. Therefore, a human should also be able to interpret the robot's nonverbal behaviour.

[1] Hannover Messe 2012: `http://www.hannovermesse.de/en/about-the-trade-show/programme/tradeshows-lineup/industrial-automation/programm/mobile-robots-autonomous-systems` (last retrieved 20.08.2012)

1.1 Example to the Situation of Interest

The following illustrative story provides an introduction to the general context of this thesis. Subsequently, reflections and resulting questions are discussed.

> *Imagine – in the near future, you buy a mobile service robot for your flat or office to assist you with various tasks. From time to time, you meet your robot while walking through or towards a narrow passage, e.g., created by furniture, hallways, door frames, or a small kitchen. Your service robot blocks the way, or drives towards you, pursuing its own goal, which it has received from you or from other people in your home or office. You just want to pass by – maybe you are in a hurry.*
>
> *For example, you are in your tiny kitchen and you want as your next task, to carry out some drinks for your friends. Your service robot has just helped mixing the drinks, but now it is blocking the doorway. How should it know that the very place where it stood a moment ago to help you has now become an unsuitable place for it to stand around while waiting for more instructions? Or vice versa, how should you know what goal your approaching robot has?*

In order to make room, this service robot needs to decide whether you just want to pass by or whether you would like to start a conversation with it. Imagine now that rather than meeting a robot, you come across another human being instead. This time you would probably just move around each other without the need to speak, even if the meeting is in a narrow passage and one initially blocks the way of the other. This illustrative story provides an idea of the challenges a robot faces in its interactions with a human being. Equally, viewed from the human perspective, challenges are also posed for the human who wants the robot to help her / him and who therefore needs to be able to understand the robot. The aim of the following sections is to set out the purpose of this thesis, to provide an overview of the research questions, lines of thought, and outline the interdisciplinary approach adopted in the research for this thesis.

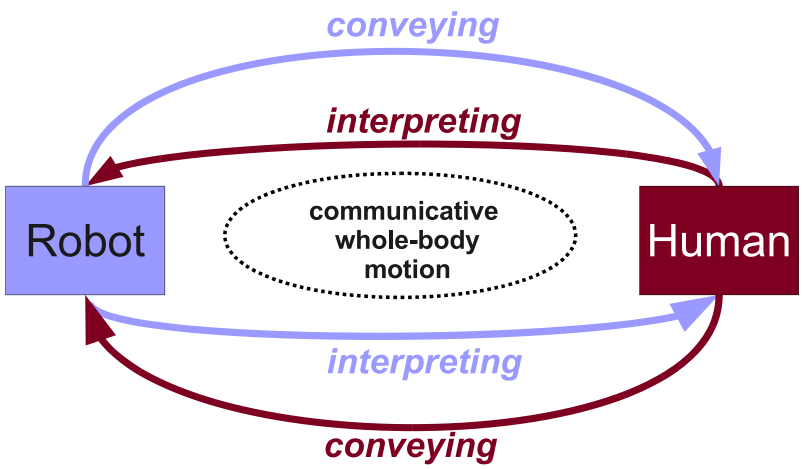

Figure 1.1: *The depicted interaction partners 'Robot' and 'Human' (boxes) have each a decoding and an encoding role of information in interaction with each other. However, as only human and robotic whole-body motion in interaction with each other is considered, the roles are named 'interpreting' role and a 'conveying' role of information.*

1.2 Methodology and Research Questions

Regarding this illustrative story, there are certainly many initial points from which one's research could start. My particular interest, however, lies in the nonverbal communication between human and robot in their interaction, in particular, the communicative potential of human - and robot whole-body motion in situations in which whole-body motion is essential to reach physical goals.

Relating back to the encounter of humans in the illustrative story above, nonverbal signals or cues would have been sent back and forth between both interaction partners, containing information which helped them to figure out as to whether or not they were in a 'passing by' situation. Very generally, interaction partners have a decoding and an encoding role in relation to interaction information, interpreting and conveying cues from whole-body motion in interaction with each other [Allwood, 2002]. Interpreting and conveying roles are fundamental elements of understanding each other's intention [Tomasello et al., 2005]. In interaction, each partner has both roles at the same time. For a smooth interaction to be achieved between robots and humans, this should also apply in their interaction with each other. Figure 1.1 displays the general roles which a human and robot in interaction should have.

Research has been conducted within the field of robotic systems. Here, robots and humans are usually engaged in a conversation and / or a tutoring situation or teaching situation [Lohan et al., 2012; Peltason and Wrede, 2011]. In these, humans show objects via different hand gestures to the robot [Salem et al., 2010; Topp, 2011]. But less research has been carried out in relation to communicative motion with the entire body. Some systems predict trajectories of approaching humans [Hermes et al., 2010] - but how should a robot interpret these trajectories?

Within the decoding or interpreting role, it is important for a robotic system not only to track human motion, but also to make sense of it. That means a robot needs to have a metric or calculus upon which it interprets or rates detected characteristics of motion of a person.

Within the conveying role, a robot, which is capable of motion with the entire body, needs to be aware of its conveyed motion. Humans interpret such motion whether or not it was intended [Breazeal and Fitzpatrick, 2000]. Therefore, any motion of a robot has an effect on the human interpretation of the robot's intent. Furthermore, knowledge of how to tweak characteristics of motion is important for explicitly designing communicative motion in robots. Kanda [2010, p.44] states in relation to nonverbal research in HRI: "It remains quite challenging to interpret the user's action and to express the robot's message". Considering Kanda's statement, a fine-grained analysis of the potential of communicative whole-body motion in HRI is missing. Therefore, the methodology for this thesis is to focus in detail on the human role of interpreting and conveying communicative whole-body motion in interaction with a robot and into the robotic role of conveying motion for investigations regarding the communicative potential of motion. Focusing on the different roles of interaction is accomplished by two research questions. These research questions cover different aspects of the interaction with either the robot or the human and are therefore treated separately.

Goal: *Fine-grained analysis of the potential of human - and robotic communicative whole-body motion in HRI*

The goal is achieved by two questions which result in two separate investigations. There are two sides to each question. Depending on the perspective on interaction, the following questions can either be formulated from the human or from the robot perspective:

Question about robot motion:
Q1: *To what extent does a human attribute intention to a robot in motion? Or asked from the other perspective; which characteristics of robot motion are important to convey the robot's next action?*

Question about human motion:
Q2: *Which characteristics or motion patterns of human whole-body motion are relevant for conveying intention towards a robot? What, in the human whole-body motion, conveys the information to predict the actions or intentions upon which a robot should act? It is also the question of how to find, define and describe human communicative whole-body motion for a robotic system to interpret?*

In short, the goal is accomplished by asking two sub-questions Q1 and Q2 to provide the information for discussing the communicative value of whole-body motions. The methodology contains therefore two separate investigations not only because there are two different questions, Q1 and Q2, but more importantly, to provide answers relating to the different roles in an interaction, cf. Figure 1.1 and Figure 1.2. For HRI, there is the robot role and the human role in the interaction.

The requirements for Q1 (robot conveying, human interpreting) are, of course, that the robot is conveying motion that a human can interpret. Investigations within Q1 are the first steps to provide an overview of the actual state of a robot conveying motion patterns which are interpreted by a human.

The requirements for investigations for Q2 (human conveying) are that the robot is present, so that the human has the opportunity to nonverbally communicate via whole-body motion with the robot. For this investigation, the robot does not necessarily need to interpret the communicative motion of the human. The focus lies on observing human communicative motion and to define human communicative motion and its characteristics. That is why, the interpreting role of the robot is not considered. However, Q2 lays the basis for representing and therefore detecting communicative whole-body motions.

Closing the loop of investigation, the gathered information will then provide a basis for discussing the potential of communicative whole-body motion in HRI. Figure 1.2 displays the roles of the interaction marked with the corresponding questions Q1 and Q2.

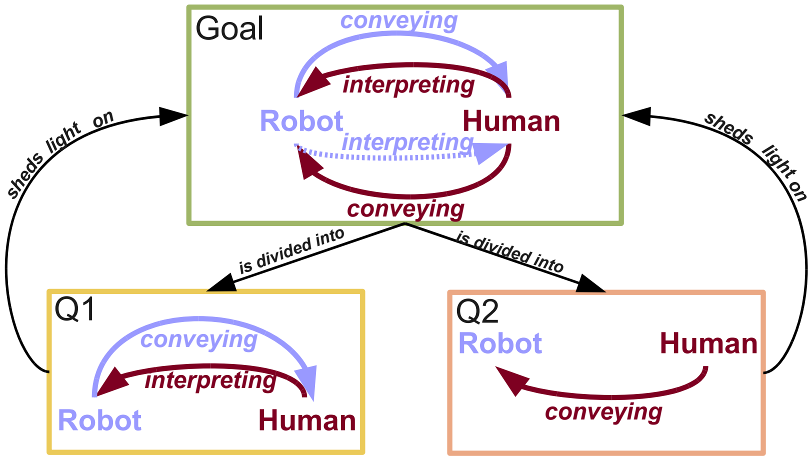

Figure 1.2: *The aim is to focus on the human role of interpreting - and conveying communicative whole-body motion in interaction with a robot (this can also be seen from the robot's perspective). To do so, the investigation is split up into two parts (main questions) Q1 and Q2. The results will then provide information for discussing each of roles in the interaction. The information for the robot's interpreting role is derived from the results of the investigation of the human conveying role (Q2). This is why the arrow presenting the robot's interpreting role, is dashed.*

1.2.1 Blocking Situation in Narrow Passages

To come back to the earlier illustrative story, not only did this introduce the research questions for this thesis, but it also provides insight into the situation of interest and challenge. The challenge is that the interacting partners have to coordinate themselves in narrow passages and blocking situations. The illustrative story can be condensed to the following summary:

The illustrative story is about nonverbal communication via whole-body motion between a robot and a human in narrow passages in which the robot is blocking the way accidentally.

This synopsis introduces not only the more precisely described topic of *communicative whole-body motions in HRI*, but also the initial situation which is considered in this thesis, namely, *a situation in which the robot is blocking the way for a human.* Both, the robot and the human have to manage their interpersonal space in order to reach their goals. This is the starting point for all investigations in the scope of this thesis.

1.3 Sketch of the Related Work

There are several facts, findings and suggestions from a range of research fields and different points of view that serve as motivation to investigate communicative whole-body motions in human-robot interaction in narrow passages and blocking situations. Subsequently, these motivational factors are presented and structured by paragraph headings. Each paragraph heading emphasises a keyword which needs to be mentioned to cover the cross-disciplinary motivation for the topic of this thesis. More detailed descriptions and definitions and an overview over the cited related work can be found in Chapter 2 - Chapter 3.

1.3.1 Human Nonverbal Communication

Of course, there are a variety of factors which influence human behaviour and enable people to act in an acceptable and predictable way for our partners in interaction, for example, social conventions, familiarity and attitude towards each other, statuses, vocalisation, the situation itself, and for this thesis in particular, body language with the entire body. Nonverbal communication is a broad term, comprising different levels of influencing variables and characteristics [Knapp and Hall, 2009]. People use means of communication that are nonverbal, especially in the coordination of joint actions [Breazeal et al., 2005]. These nonverbal means are not restricted to hand gesturing, they concern the whole body [Oberzaucher and Grammer, 2008]. Especially in 'passing by' situations in HRI, body language, in terms of whole-body motions, provides informative cues for deciding what to do [Butler and Agah, 2001; Peters et al., 2011]. The examination of the communicative potential of motion is motivated by several facts. Generally, it is motivated by the fact that human communication comprises more than only words. There are nonverbal characteristics of communication which accompany human speech and those which stand alone and / or substitute for spoken words and / or which communicate different messages compared to the message which is transmitted in speech, in particular body language [Knapp and Hall, 2009].

1.3.2 Human Attribution of Intention through Motion

On a daily basis, people have to coordinate their whole-body with other people in different environments. Moving and stable obstacles and moving and motionless humans are encountered. These factors create the need to predict their paths and the intention of other humans in order to safely move from one place to another [Frith and Frith, 2006]. In order to *share space with others in narrow environments*, insight into the interaction partner's intention is helpful in anticipating the other's next action and in acting in time. Humans do not need to speak to each other in order to pass by successfully. The intention, which is hidden in the human body motion, is decoded and interpreted in a natural and spontaneous manner. This is an important part of our nonverbal communication [Barrett et al., 2005; Pavlova, 2011; Castelli et al., 2000; Crick et al., 2007].

Furthermore, humans are able to attribute intentions and social role to any kind of object or animate creature by simply watching their motion signatures or patterns [Heider and Simmel, 1944]. Additionally, social conventions like different interpersonal zones help in attributing intents, [Hall, 1966] and cf. Chapter 3. Humans are also able to attribute intentions to goal-directed, translational and rotational motion which represent abstracted point clouds or single objects (square, triangle) representing humans in motion. Motion is a powerful way of communication as Heider and Simmel have shown in 1944. Therefore, communication via motion should be transferred to HRI too, as robots are at least able to move in the way Heider and Simmel reported their triangles and squares to move. Therefore, the communicative potential of whole-body motion of a robot in HRI is investigated in this thesis.

1.3.3 Human Communicative Motion towards a Robot

The HRI community has recently started to investigate human natural nonverbal communication in HRI setups [Kanda, 2010]. Human-Robot Interaction can learn from human interaction [Pacchierotti et al., 2006]. Takayama and Pantofaru [2009, p.5495] state that the Media Equation (– "people interact with computers as they would interact with humans [...]) may become increasingly true for human-robot interaction, where the computers [...] take action in the physical human environment" cf. also [Reeves and Nass, 1996]. The authors also state that human interaction paradigms are not necessarily the same for HRI [Takayama and Pantofaru, 2009].

To provide a better overview, human communicative whole-body motions are also investigated in a HRI setting – not in a human interaction setting.

This approach is supported by Hüttenrauch et al. [2006b] who report on small whole-body motions from humans towards a robot and suggest that these have a communicative purpose.

1.3.4 Narrow Passages in HRI

As illustrated in the earlier story, blocking situations in narrow passages are relevant. They occur several times in people's homes caused by furniture or other people and robots. Hüttenrauch et al. [2009] brought the mechanoid robot[2], Minnie, to people's houses and flats and observed several narrow passages in each home. In these narrow passages, the human came close to the robot, because the robot was accidentally blocking the way. The robot was not aware of the fact that it blocked the way for the human who was guiding Minnie around the house. While a lot of HRI research focuses on eye-gaze, hand gestures and facial expression, less research focuses on motions with the entire body.

1.3.5 Social Robotics

The research for this thesis is situated in the field of social robotics. Here, robots in this sense are companions to humans, fulfilling a range of different services in the household or office, collaborating and undertaking tasks with and without the human. Per definition, social robots exhibit some human social traits to better interact with their human interaction partners [Fong et al., 2003]. One similar trait between robots and humans is goal-directed motion. The mechanoid (mechanical-looking) robots, which are used within my research, are able to move around. Section 2.2 presents a general definition. Figure 1.3 depicts two state-of-the-art and mechanoid robots, Snoopy (left) and BIRON (right), which are used for the studies, examining the communicative aspect of rotational and translational motion. A more detailed description of each respective robot is presented in the corresponding description of the study setting; Section 5.1.4 (BIRON) and Section 6.1.3 (Snoopy).

[2] A mechanoid robot is a mechanical-looking robot cf. Section 2.2

Figure 1.3: *The mechanical-looking robots Snoopy (left) and BIRON (right) are used within the studies examining the communicative aspect of motion in HRI. Section 5.1.4 provides more information on BIRON and Section 6.1.3 more on Snoopy. These robots are able to rotate their body and move forwards and backwards. Subtle motions of these robots can communicate their intent, see Chapter 3.*

1.3.6 Robot Communicative Motion towards a Human

Watzlawick's known axiom, *"One cannot not communicate"* states that a human cannot not communicate to other people, no matter how one behaves; everything is communication [Watzlawick, 2011, p.15] and [Watzlawick et al., 1967]. Transferring this axiom to HRI, subtle motions of moving robots can communicate intention. Breazeal and Fitzpatrick [2000] state that motion of a robot and a human in interaction is always present and will be interpreted, whether or not it was intended by the human. In addition, Hüttenrauch et al. [2006a] suggest that robots should use small and subtle motions to influence human users to position themselves in a better way for the robot to interact with.

1.3.7 Robot Motion

For all mobile service robots, motion from one place to another place is the essential ability [Steinfeld et al., 2006]. Simple translational and rotational motion is comparable within a range of robots. Figuratively, it is the lowest common denominator. Therefore, investigating these motions is interesting for a wide range of robots. Furthermore, this kind of motion is highly comparable with human translational and rotational motion. Considering the ability to attribute intentions to translational and rotational motions of objects [Heider and Simmel, 1944], motion of a robot is also expected to communicate intention to humans.

Naturally, motion also has a navigational aspect. Especially in robotic research, it is essential to ensure safe navigation around humans. In human research, the two areas, navigation and communication, are clearly separated. In robotic research however, they are not so clearly separated, and the communicative aspect of motion is only considered from the navigational view and mixed view [Kirby, 2010]. There is limited research on the communicative aspect, so far. This thesis sets out to consider the communicative aspect of motion, cf. Section 2.3. It is motivated by the fact that every step, every motion, and especially an unexpected motion of the robot, is sending communicative signals and cues to the interaction partners [Hegel et al., 2011].

The mentioned findings and suggestions serve as motivation to examine communicative whole-body motions during human - robot encounters in narrow passages in which the robot blocks the way for the person. Both the human perspective and the robot perspective in this encounter are investigated to find, define and analyse motions which are used for communication. The position of the motivational facts is illustrated by Figure 1.4 (p.12). Two semicircles consist of arrows and boxes which display the role which a robot and a human can take in interaction with each other, similar to Figure 1.1, Figure 1.2 and Figure 1.5. The motivation and the corresponding questions are assigned to the corresponding roles and parts in the semicircles. The displayed directionality also emphasises the two parts or investigations within this thesis: the upper semicircle stands for the 'robot motion towards a human' and the lower semicircle stands for 'human motion towards a robot'. These arrows are displayed throughout this thesis to stress the actual focus. The goal is not explicitly presented in this circle as investigations for Q1 and Q2 and their results represent the goal to investigate communicative motion in HRI.

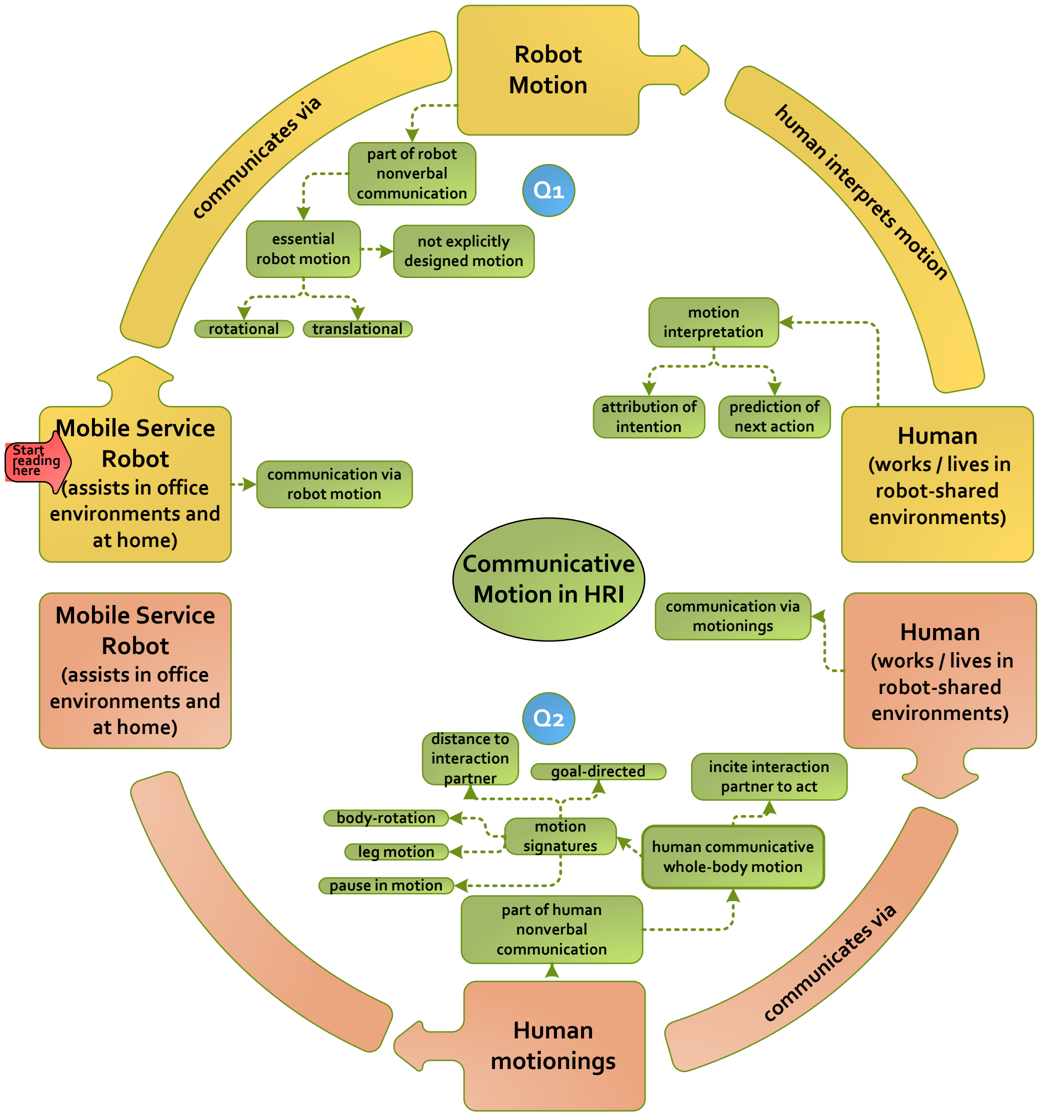

Figure 1.4: *This sketch illustrates the methodology of this thesis with a circle. The circle displays the roles in HRI, which are in this thesis separately investigated. The upper semicircle emphasises the focus on the robot motion on the one hand. On the other hand the lower semicircle emphasises the focus on human motion. This is why the arrows in circle point only in one direction and robot and human boxes are displayed twice. The displayed directionality also emphasis the two parts or investigations within this thesis:* `robot motion towards a human` *and human motion towards a robot. Furthermore the incorporated motivation and description of motions help to align future and already stated explanations. The robot interpretation is left out on purpose as it is not subject matter of this thesis, cf. Figure 1.5 for the methodology of this thesis.*

1.4 Scope and Aims

Motion of the entire body as part of nonverbal communication is still a general context. To be more precise, the focus lies on motion with the entire body or machine that incites an interaction partner for spatial coordination. I call these motions 'motionings'. Chapter 2 and especially Section 2.6 provide a longer definition. Regarding the illustrative story on the basis of such motioning, the body motion of the human could have incited the robot to make room. These motions are always somewhat goal-directed and can also be unwittingly conveyed. Interpreted in the right way, they provide information about the interaction partner's intention cf. Chapter 2 - Chapter 3. Communicative potential of whole-body motions is examined on the basis of the situation that a robot is unintentionally blocking the way for a human interaction partner.

Managing interpersonal space is a daily event between persons. Furniture and narrow environments cause several narrow passages in which a robot and a human potentially meet. Especially, in situations like these, the already present motion of the interaction partners is interpreted and reveals the other's intention. Therefore, the general aim is to improve this situation by figuring out: (Q1): how and which motion patterns of a robot are interpreted easily and (Q2): how and by which means humans display their intent through motion to a robot. The investigations for Q1-Q2 are conducted to isolate the communicative whole-body motion, to verify its presence and to give detailed definition on motionings for HRI from the human perspective towards the robot and vice versa. Collected video data and questionnaire data and its examination provide answers to the questions of how to improve robotic whole-body motion to HRI. The basis for the exploration of this field of research is set out in Peters et al. [2011]; Peters [2011] and is taken to completion in this thesis. Figure 1.5 (p.14) summarises the methodology, questions and motivation of this thesis. The title of this thesis summarises the introduction: *Spatial management via communicative* ***whole-body motion*** *in* ***human-robot*** *shared* ***narrow environments***

Butler and Agah [2001, p.200] conclude their article on HRI studies on robot approaching and passing: "A personal robot that is placed in the home would need to communicate with humans in as many ways as possible." Therefore, the goal of this thesis is to investigate the 'natural' use of whole-body motion as means of the communication. This means when investigating human motion that human communicative whole-body should be investigated when they are naturally conveyed. In other words

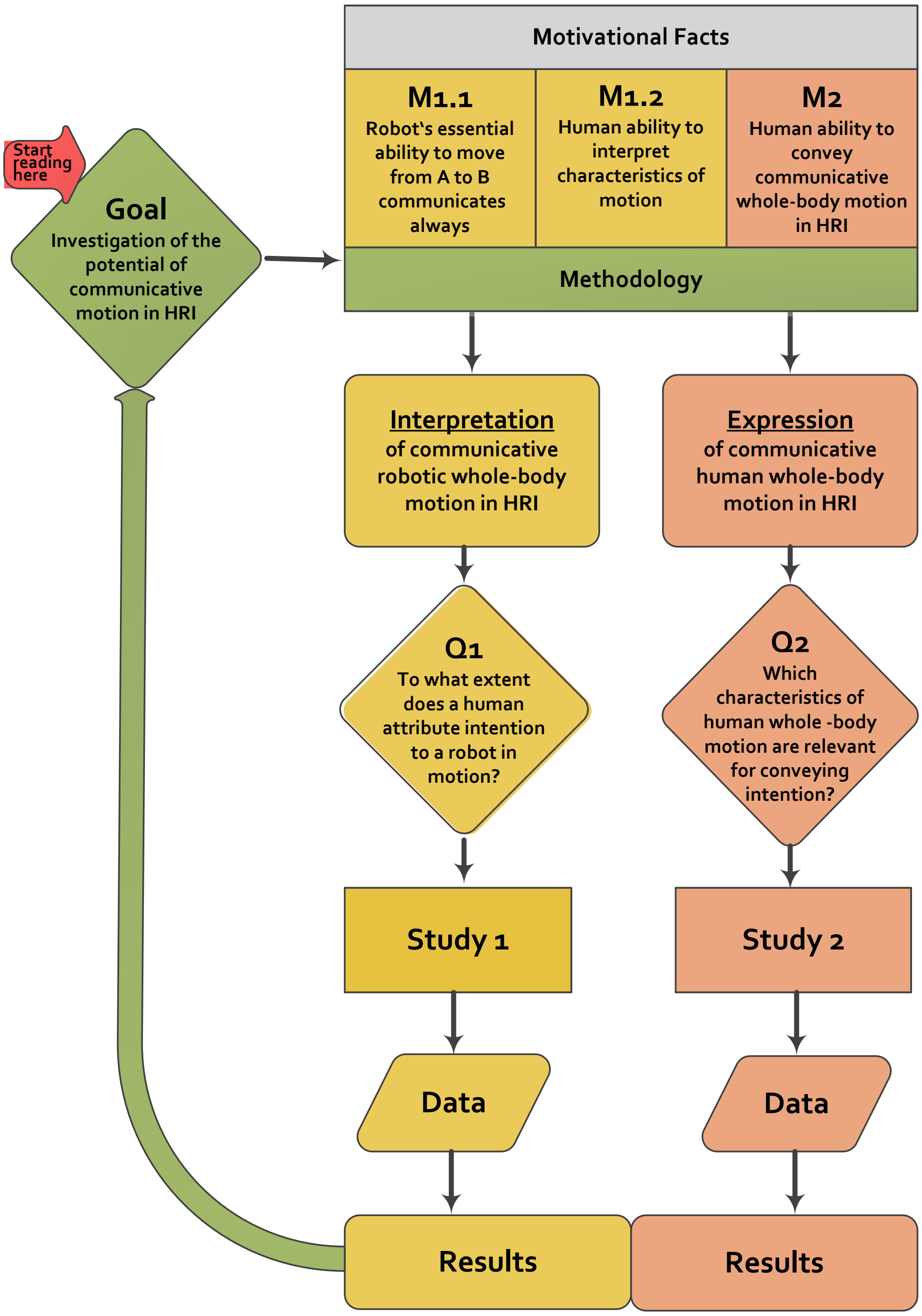

Figure 1.5: *This figure displays the methodology of this thesis. The driving goal is accomplished by two sub-questions Q1 and Q2. The methodology is to provide two separate investigations not only because there are two different questions Q1 and Q2 but more importantly the questions provide information about two different perspectives on HRI. There is the robot role and the human role (or perspective) in the interaction, cf. Figure 1.1 - Figure 1.4. The outcomes from both investigations (Q1 - Q2) are combined and discussed in the end. Furthermore, this figure displays some facts and statements within the circle which motivate to ask these questions.*

human participants of the studies are not allowed to practise any kinds of body language in interaction with the robot nor are they allowed to know what the focus of this thesis is. To emphasise, the thesis is ***not*** aiming at inventing a new language of commands of body motions which needs to be taught to the human partner in order to interact with the robot successfully. The requirement for the investigation of robot motion is that the participants of the relevant study should not have been introduced the way a robot could communicate via whole-body motions nor are participants allowed to know the goal behind the investigation beforehand. Moreover, this approach is somewhat different to a standard computational approach of building a robotic system. This thesis is rather fundamental research aimed at finding ideas of how to improve nonverbal communication via motion in robotic systems.

1.5 Conclusion

The introduction addressed the methodology and research questions of this thesis. The relatively short paragraphs of motivational facts, findings and suggestions give an overview of the reasons for asking these guiding research questions and writing this thesis. Moreover, the motivational sections provided an overview of the cross-disciplinary related work and provided the basis for the next chapter.

1.6 Outline of this Thesis

The following paragraphs provide a short summary of further chapters of this thesis.

- **Chapter 2 (Definitions for the Scope of this Thesis)** presents, a range of definitions, limitations and dissociations from keywords, such as HRI, communicative whole-body motion, and motionings, which were already mentioned in Chapter 1. The preliminary definition of communicative whole-body motion and motionings are the most important sections of Chapter 2.
- **Chapter 3 (Cross-Disciplinary Related Work)** presents the large amount for cross-disciplinary work which was introduced shortly in this Chapter. The chapter presents the key aspects of motion interpretation and expression of motion within interpersonal space from human-human interaction and human-

robot interaction. Furthermore, this chapter presents ideas of how to represent motions for robotic systems.

- **Chapter 4 (Methodology of the Conducted Studies)** presents the methodology for the conducting the studies. The studies are conducted as observational and exploratory case studies.
- The **Chapter 5 (Investigating Robotic Motion Patterns)** presents the description and results of the conducted study on robotic motion patterns. This study provides insight which motion patterns or which characteristics are suitable to convey the robot's intention to humans.
- **Chapter 6 (Investigating Human Motionings)** presents the description and the results of the conducted on human motionings. This chapter is providing a detailed overview of several characteristics of a human in motion relative to a robot. The chapter includes among other analyses the examination of characteristics of the temporal aspect of motionings, and characteristics such as, the relative orientation and relative position of the person, the change of distance and trajectory of motion.
- **Chapter 7 (Contributions)** provides a detailed definition of motionings enriched with the results of the studies. Furthermore it summarises the amount of small results (presented within the studies) with three heuristics. These heuristics are stated to provide pieces of advice of how to utilise the gathered information on the potential of communicative whole-body motions as a means of communication for robots.
- **Chapter 8 (Ongoing Research and Solutions to the Limitations)** presents ongoing research which is currently conducted to advance research in field of communicative whole-body motions in HRI. Moreover, this chapter provides solutions for some of the thesis' limitations.

Chapter 2

Definitions for the Scope of this Thesis

This chapter serves to clarify, disambiguate and define terms and concepts used which are essential for this thesis.

Research in the area of HRI is typically cross-disciplinary. Each associated discipline has its own way of viewing and emphasising notions and concepts [Dautenhahn, 2007b; Lohse, 2010]. Hence, the following definitions are taken and are developed for the area of HRI and its associated disciplines.

Outline of this Chapter In this chapter, *Human-Robot Interaction* (HRI) is limited to the interaction between one robot and a human in a physical embodiment which shares space with the robot.

Subsequently, the general class of *wheeled service robots* which are used in this thesis as interaction partners are presented.

The ability to move from one place to another and assist humans in their daily work at home or in the office is introduced as a key aspect of such robots. That is why the ability to navigate through undecided environments is essential for robots. However it is not the focus of this thesis. Here, *the focus lies on the communicative aspect of motion.* Hence *whole-body motion* is introduced as a part of nonverbal communication and as part of spatial coordination. The key aspects of communicative human and robotic whole-body motions are defined and disambiguated.

*The term **motioning** stands for a communicative whole-body motion which incites an interaction partner to act and that incites an interaction partner to attribute intention to the person / robot conveying.* This term is created on the basis of the term *spatial prompting*, defined by Green [2009].

Furthermore, the term *natural behaviour* is discussed and disambiguated from implicit communication.

The next section addresses the situation on which the focus of this thesis lies, briefly introduced in the illustrative story of Section 1.1: the situation in which a robot blocks the way of a person who wants to pursue her / his path past the robot in a *narrow passage*. This is a frequent but specific HRI situation because it is crucial to spatially coordinate each other in narrow passages. The blocking robot presents the reason that a human needs to spatial coordinate with the robot. Spatial coordination includes predicting (interpreting) and conveying whole-body motions.

2.1 Human-Robot Interaction

This section presents a definition and a limitation of Human-Robot Interaction (HRI) essential for this thesis. Generally HRI has many fields of application therefore different types of robots are used. Consequently, the definition of HRI is limited to the category of robot which is used throughout this thesis' investigation.

According to sociologists like Goffman or Luhmann, interaction is a subordinate part of communication [Goffman, 1959; Krause, 2005]. Both Kieserling [1999] and Luhmann [cited in Krause, 2005] define interaction as communication which requires the presence of people. Interaction is a bidirectional interplay of people (at least two) who are able to perceive each other. Luhmann explains that, in an interaction the mutual perception or communicative reachability can take place via various channels, for example via body motion, speech or both [Krause, 2005]. Although these authors do not cover the case of human-robot interaction, definitions in the area of HRI are quite similar. A fitting but general definition of the research within HRI is given by Fong et al. [2001, p.256]. The authors summarise research in human-robot interaction as "the study of humans, robots, and the ways that they influence each other". The interactional process between humans and robots is in the focus of this thesis.

Hence, interaction requires communication of some kind, between humans and robots [Goodrich and Schultz, 2007]. In that sense and for the scope of this thesis, the terms “interaction” and “communication” are used interchangeably.

Within HRI there are different kinds of interactions with a robot. Therefore, Takeda et al. [1997] and Thrun [2004] state that HRI research can be classified by distinct definitions of areas of research within HRI. An appropriate classification for this thesis on the basis of these definitions is: *HRI is intimate and direct.*

Intimate HRI means that both partners of the interaction have to be physically embodied and physically present in same room. If this is guaranteed, then the interaction is multimodal. Also the entire body is involved in such a communicational process as opposed to the other definitions: loose (interaction partners are not in the same room - that means interaction partners do not need a physical body) and collaborative (involving more robots to complete tasks) [Takeda et al., 1997].

HRI is direct when the information flow is bidirectional [Thrun, 2004]. Both partners exchange information in the interaction, opposed to indirect HRI in which the robots pass on information concerning their environment and the person, controlling the robot, e.g., in the case of unmanned aerial vehicles (UAVs) and unmanned underwater vehicles (UUVs).

Dautenhahn [2007b] classifies the approaches of HRI research into three different areas: human-centred, robot-centred and robot-cognition-centred. Human-centred HRI is, as the term implies, research from the human point of view in which the robot needs to behave appropriately and in a manner which is comfortable for the human. In order to achieve this, the robot needs to communicate in a human-like way [Dautenhahn, 2007b]. The robot-centred approach views the robot as a social entity programmed to have its own agenda. This means that the robot only helps the human to satisfy its own goals. The robot-cognition-centred approach focuses on the robot as an intelligent system and is primarily concerned with modelling the system (decision making, problem solving).

2.1.1 Human- and Robot-Centred Approach

In my opinion this thesis is not easily classified into one of these themes, as I think the human-centred approach does not exclude the robot-centred approach. If the robot is seen as a social entity with own goals and intentions, it could still act in a human-like way and a comfortable way for the human. A robot would even be perceived more human-like if humans believed it to have the ability to think on its own accord and have goals of its own. For example small motions like small steps or other movements like licking lips before actually going somewhere or eating something tasty are found to make characters more lively and create an impression of thinking cf. [Animation Principles in Lasseter, 1987; Thomas and Johnston, 1995] and cf. Chapter 3 especially Section 3.3. This thesis approach is human-centred and robot-centred at the same time. It is human-centred because the human interacting with the robot plays a role and above all needs to be comfortable with the robot, therefore the communicative potential of communicative whole-body motion is investigated. The human is conveying information via whole-body motion and is interpreting robotic motion. Using these human abilities in HRI will enrich the interaction and make the communication more human-like. Also the robot plays a role in the interaction as it conveys motion thereby making these motions more predictable and legible for the human which makes the human more comfortable with the situation. A way of doing so is to create motions that reveal an intention or an internal goal and can be interpreted by the human. Therefore this thesis presents fundamental research within the human- and robot-centred theme in HRI.

2.1.2 Different Kinds of Robots

Interaction with a robot is also dependent on the kind of robot taking part in the interaction. Robot types range from dinosaur (PLEO[1]) or, dog (AIBO[2]) appearances, to small human-like types like ASIMO[3] or NAO[4] and life-like robots like Geminoids[5] to mechanoid robots like industrial robots or UAVs[6] (Unmanned Aerial Vehicles) or UUVs (Unmanned Underwater Vehicles). Another group of robots are robotic cars, such as Stanley, which won the DARPA challenge [Thrun et al., 2006]. These robots have different tasks to fulfil within different fields of application (see excerpt of HRI

[1] For pictures of the respective robots see following websites: PLEO: `http://www.pleoworld.com/pleo_rb/eng/index.php` (last retrieved 20.08.2012)

[2] Sony AIBO is not sold any more

[3] ASIMO. `http://asimo.honda.com/` (last retrieved 20.08.2012)

[4] NAO: `http://www.aldebaran-robotics.com/en/Pressroom/About/NAO.html` (last retrieved 20.08.2012)

[5] Geminoids: `http://www.geminoid.dk/` (last retrieved 20.08.2012)

[6] UAV: `http://www.microdrones.com/index.php` (last retrieved 20.08.2012)

applications here: Kim et al. [2009, PLEO], Weiss et al. [2009, AIBO], Yasumoto et al. [2011, ASIMO], Cohen et al. [2011, NAO], Bartneck et al. [2009, Geminoid], Peschel and Murphy [2011, SUAV]). There are also non-animal or non-human-like robots in appearance which share similar tasks or fields of applications, namely, the wheeled service robots. This class of robots is described in the following section and used throughout this thesis.

2.2 Wheeled Service Robots

The robots, BIRON and Snoopy, which are used for study purposes within this thesis, are mechanoid, and wheeled service robots. Walters [2008] defined mechanoid robots as robots having a mechanical appearance which is not overtly human-like in appearance. Usually, these robots have wheels to drive around instead of legs, a laser range finder, a base frame with one or more cameras, and microphones. The robots, BIRON and Snoopy, used to study the phenomenon within the scope of this thesis, are of such a type. Pioneers (Snoopy[7]), PeopleBots and PatrolBots (BIRON[8]) by Adept MobileRobots[9] robots are often described as mechanical, mechanistic or mechanoid robots [Walters et al., 2005b, 2007, 2008; Pacchierotti et al., 2006; Takayama and Pantofaru, 2009; Syrdal et al., 2010].

Steinfeld et al. [2006] states that motion is a fundamental skill. These robots should be able to navigate from one place to another. This skill enables the robot to use its motion as a nonverbal cue in human interaction and it is taken as a communicative approach by a human even if it is not designed as such, cf. Chapter 3.

2.2.1 Robots are Anthropomorphised and Humans behave like Humans

Remarkable is that humans communicate with robots in a similar way as they do with other humans. That is a phenomenon, in which the *media equation theory* provides insights. *The Media Equation Theory* by Reeves and Nass [1996] state that people

[7]For pictures of Snoopy see Figure 1.3 and Figure 6.4.

[8]For pictures of BIRON see Figure 1.3, Figure 5.2, and Figure 5.3.

[9]See `http://www.mobilerobots.com/Mobile_Robots.aspx` for pictures of Pioneers and PatrolBots, PeopleBots are not sold any more (last retrieved 20.08.2012)

attribute social behaviours to media like computers, TVs and other things depending on behavioural cues. Behaving socially towards, or attributing social roles happens in automatic or spontaneous ways [Reeves and Nass, 1996]. HRI research, particularly, in social robotics where people share environments with robots or where robots are applied to work collaboratively with humans and / or assist humans in their daily lives, took the media equation as a basis for their research to start and justify human interaction as a basis for HRI [Fong et al., 2003; Walters et al., 2005a; Harris and Sharlin, 2011; Saulnier et al., 2011; Takayama and Pantofaru, 2009]. The media equation is a general communication theory. With the media equation theory certain hypotheses about, how human-robot interaction works, can be formulated. Naturally each phenomenon has to be established separately [Dautenhahn, 2007a]. Although mechanoid robots do not appear human-like, certain equipment on the robot, like cameras and screens can be anthropomorphised according to the Media Equation in Reeves and Nass [1996]. Furthermore, Dautenhahn [2007a, p.104] discusses that "human anthropomorphize not only nature, but basically anything around them: we might talk to our broken coffee machine, praise our car if it starts on a very cold morning, or pretend that a stuffed horse is a living animal when playing with our children. It is the very nature of human beings to be social." That is why, for the scope of the investigations of this thesis, it is expected that humans interpret robot motion and that humans behave in their "natural" human way interaction with the robot.

2.2.2 Social Robots

Fong et al. [2003] and Dautenhahn [2007b] state that social robots are designed to be assistants, companions, pets or servants. These robots are required to be socially interactive. That means they should send easily readable signals to the humans in order to inform them about internal states and interactional statuses. There are various channels for expressing these signals or cues, including vocalization, facial expression or body language [Fong et al., 2003]. Moreover, social robots need to be aware of the human internal states [Dautenhahn, 2007b]. Fong et al. [2001] and Rosenthal et al. [2011] also argue that these robots should not be regarded as tools but as companions to receive help from or to collaborate with humans. Rosenthal et al. [2011] reported that their robot assists in an office environment and asks humans for help in case it encounters an unsolvable problem, e.g. an unidentified obstacle, which is blocking the robot's way. Moreover, social robots assist in homes, offices, shops and museums to guide people around or fetch and carry items [Clodic et al., 2006; Dautenhahn, 2007b; Ludewig et al., 2011; Poeschl et al., 2011; Topp, 2011].

2.2.3 The Robots BIRON and Snoopy

The studies, which are investigated within the scope of this thesis, are conducted with the field and tasks of social robotics in mind. The wheeled mechanoid service robots BIRON and Snoopy are used as office robots in this thesis' investigations. BIRON and Snoopy are described in the corresponding chapter of investigation, cf. Section 5.1.4 (BIRON) and Section 6.1.3 (Snoopy).

The robot BIRON, which is not only used in this study as a social and wheeled service robot, is applied in 'home tour' studies and the RoboCup@home league [Wachsmuth et al., 2010; Lohse, 2011]. In these home tour studies and also in the RoboCup@home league, BIRON has several tasks to fulfil. One of the tasks is that the robot is guided around by a human, who presents items and rooms to the robot to memorise and find or fetch these items later on. The quintessential challenges are that in these environments a robot encounters not only different situations but also different humans, who might *not* be introduced to the verbal commands of a robot. Additionally, even if verbal commands are known they might not work due to the noisy background. Solutions for the robot in interaction with a human are to use more channels of communication or a different modality to communicate in those situations. Interpreting and conveying nonverbal cues help the robot not only to be aware of but also to express its own goals more clearly for human bystanders and users. This is one of the reasons, why the communicative aspect of motion is in the focus of this thesis.

In the style of these home tour scenarios and possible tasks in the RoboCup@Home League, the robots BIRON and Snoopy are used as office robots during the studies reported in this thesis [Peters et al., 2011; Topp, 2011; Peters, 2011].

2.3 The Communicative Aspect of Motion

This section presents the argument that motion should not only be seen as a means of navigation but also as part of the nonverbal communication. From a roboticist view, the ability to navigate is a key aspect for mobile robots in interaction with humans [Steinfeld et al., 2006]. Without the ability to navigate from one point to another a lot of tasks which such a robot should fulfil would not be possible.

Considering the communicative process in the human-robot interaction, everything that is done and spoken, influences the interaction partner [Breazeal and Fitzpatrick, 2000]. Hence, there is always a communicative aspect of motion even if it is only the motion from one place to another, especially, when social robots interact with humans. This aspect is increasingly regarded in HRI research.

For all mobile robots the navigation around obstacles is essential and is a well established research area. From big machines in industrial setups to small vacuum cleaners in people's homes, robots need to be able to move and encounter obstacles. In this context Borenstein and Koren [1989, 1990] treated humans as static obstacles. Progressively, approaches using obstacle avoidance algorithms took robot dynamics (acceleration, deceleration) into account [Simmons, 1996]. However these approaches are problematic within human-robot interaction situations because humans do not behave similarly to static objects at all. That is why, Fiorini and Shiller [1998] treated humans as dynamic obstacles in their navigational approach. Treating humans as dynamic obstacles guarantees that humans will not be run over, but does not account for spatial joint coordination in interaction in different situations, e.g. where people come purposely close to robots while showing items in a small room.

Recently, the awareness developed in the HRI community that humans are not comparable to dynamic inanimate objects. The future path of dynamic inanimate objects is completely predictable. The same predictability cannot be applied to humans. They are driven by other forces. Kirby et al. [2009] presented human aware navigation. The system COMPANION considers a social convention (keeping on the right side while driving) and proxemics (different personal spaces) [Kirby, 2010].

There is further research, which investigates different situations and their conventions, which robot navigation needs to take into consideration: Nakauchi and Simmons [2002] researched how humans stand in line and transferred this behaviour to a robot. Holthaus et al. [2010] tested different greeting or acknowledging behaviours of a stationary robot towards approaching humans in relation to different interpersonal distances cf. also Section 3.5 - 3.6.

Within these approaches, the navigational part fades into the background. Mere obstacle avoidance and navigation is essential but there is more there is the communicative aspect of motion. Considering the communicative aspect, one needs another perspective on motion. For the purpose of illustration: the goal to navigate to a place B from a place A becomes less important then *the way* this motion is executed. For example, jerky motion, pauses in motion or smooth motion might be interpreted in different ways: Moon et al. [2011] report that hesitations in motion can be interpreted as uncertainty or as means to attract attention. Also, robot motor actions are also perceived to be semantically rich, even if they are not intended to be [Breazeal and Fitzpatrick, 2000; Fong et al., 2003; Dautenhahn, 2007b; Mutlu et al., 2009]. Moreover, small communicative movements like nodding, eye gazing and hand gestures have been identified to support the interaction [Breazeal et al., 2005; Mutlu et al., 2009]. Also whole-body motions as communicative means were observed from a human towards a robot [Peters, 2011].

An area in which motion is used as means of nonverbal communication, is the management of interpersonal space between people. The next sections define a way of spatially coordinating via whole-body motions. First of all whole-body motions will be defined.

2.4 Whole-Body Motions

This section defines the term communicative whole-body motion (WBM), for the scope of this thesis. The term whole-body motion encompasses both human whole-body motion and robotic whole-body motion.

The term whole-body represents the entire human body or the entire robot body. The entire human or robot is considered as one entity in space which has the ability to move, cf. Figure 2.1. Figure 2.1 displays a transparent cylinder around a sketched human and around a sketched robot. The cylinder represents the meaning of the term whole-body or entire body - no other motions with parts of the body are considered. The cylinder stresses that the human or robot body is observed as one entity throughout this thesis. The human entity has the possibility to move in all directions whereas there are limitations on the robotic way of driving: The robots, used in this thesis, have only the ability to move forward in the direction they are facing[10] due to

[10]Snoopy has the ability to move also backwards.

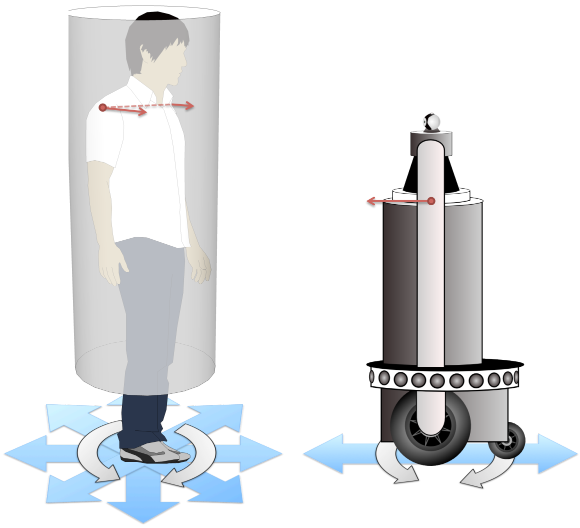

Figure 2.1: *Displayed is a sketch of a human and a robot. The human has a transparent cylinder around its body (head to its ankles). The cylinder represents the meaning of the term whole-body or the entire body. It is displayed to demonstrate the similarity of human whole-body and robotic whole-body motion. Whole-body or entire body means that the human as such is observed as one entity throughout this thesis. This entity has the possibility to move in all directions (within the horizontal plane) and rotate its body around its vertical own axis. The considered motions of the entity are the translational and rotational motions. The blue arrows underneath the drawing display the translational motion and the circle on top of the blue arrows represent the rotational motion. Translational human motion is realised by a movement of the whole-body via feet (and legs) with the intention to change position, e.g., steps. To emphasise the realisation of this motion, the lower legs and feet are displayed without the cylinder in the sketch. The rotational human motion, in this case, is an orientating or rotating movement of the body around its own axis. The shoulder joints of a human and the feet are the indicator of where the human is orientated to. Regarding a mechanoid robot its translational motion is any kind of motion with the wheels, e.g. driving. Snoopy and BIRON have a differential drive and can only turn and drive forward or backward in the direction they are facing. Thus the robots presented in this study have the ability to drive forwards and turn on the spot (plus in Snoopy's case, drive backward)). That is why, only forward and backward arrows in blue are displayed. The rotational motion is also displayed by the white arrow around the robot's axis. Any edges comparable to shoulder joints of the robot indicate the orientation of the robot, see the red arrow on the robot.*

their differential drive. They have to rotate first for any other direction. Thus, these robots are able to turn on the spot and drive curves, while they are driving forward. Neither movements with single joints from a robot nor a human are not considered. Considering the human body, the head, trunk, and arms become one entity. The legs and feet of a human are used to move her / his body. Comparatively, wheels of a robot are used to move the robot around. The human with her / his whole-body motion or the robot with its whole-body motion can be considered as a moving entity in space. Generally, there are characteristics which describe a moving entity in space. An entity in a defined space has a position and an orientation. Through motion of its body, it can change position. With a change in position the entity has a trajectory that is the direction of motion. The entity in motion can also change its orientation and it has a distinct speed. In interaction with another entity, the entity has a spatial proximity to the interaction partner (distance) which can also change through the motion of the entity. This definition conforms to the understanding of whole-body motion in Barrett et al. [2005] and Van De Weghe et al. [2005] cf. also Section 3.4. For the scope of this thesis, the terms "whole-body motion", "motion with the entire body", and "body motion" are interchangeably used for the motion of the entire robot.

There are also other definitions of whole-body motions which do not conform to my definition of whole-body motion. The term whole-body motion is also used to describe motion with more than one part of the body, e.g., a piano player's hands and feet interact with different parts of the piano. Currently, console games use this kind of whole-body motion in their games: players have to jump on a foot mat and press a button on a remote control to play the game [England, 2011].

2.4.1 Whole-Body Motions Part of Nonverbal Communication

A very general working definition of nonverbal communication is, "communication that is effected by means other than words" [Knapp and Hall, 2009]. There are so many components of communication that interplay with each other that a classification into nonverbal and verbal communication might be a good working approach for this thesis, but it is not sufficient if one wants to be precise as there is not a clear separation possible [Knapp and Hall, 2009]. Nonverbal components are part of the entire communication or interaction process. Nonverbal and verbal features can be interlinked, for example, speech and prosodic features or language dependent hand gestures [Gill, 2004]. But there are also nonverbal characteristics, which are not necessarily connected to spoken words. These substitute words and have a communicative function accompanied by unspoken mutual understanding [Knapp and Hall, 2009; Green, 2009; De Jaegher, 2009; Gill, 2004]. Eye gaze, gestures, facial expressions and whole-body motions are such characteristics. De Jaegher [2009] suggests that motion as communicative characteristic in interaction is foundational, especially in situations in which the interpersonal management of space is important, cf. also the illustrative story in Section 1.1. De Jaegher [2009] states that patterns of interpersonal coordination through whole-body motion can influence the individual and do not need any accompanying words. As well as words, nonverbal characteristics can be also ambiguous in attribution. They are context or situation dependent. For example, a smile can be an emotional expression, attitudinal message or a listener response to encourage communication, a fake or a scripted smile. A step towards a person could be either a comforting act to provide closeness or an aggressive act that urges the other to step back.

Naturally, a question comes to one's mind, namely, *what characteristics of whole-body motion describe the whole-body motion and make it unambiguously legible meaning also unambiguously interpretable. This is the unanswered challenge that summarises the motivation for this thesis' research and the motivation for asking the guiding questions (Q1 and Q2) the way they were asked* and which also has motivated researchers from human interaction and human-robot interaction before me to contribute to this challenge cf. Heider and Simmel [1944]; Hall [1966]; Barrett et al. [2005]; Crick et al. [2007]; Takayama et al. [2011, and more]. Their research and that of others will be presented throughout the thesis and especially in Chapter 3.

2.5 Spatial Coordination via Spatial Prompts

In the previous section whole-body motions were defined. These whole-body motions were defined as they play a communicative role in the management of interpersonal space between people. In the field of HRI research, the term *spatial prompting* was coined by Green and Hüttenrauch [2006], cf. also Hüttenrauch et al. [2006a,b]; Green [2009]. Spatial prompting means that an interaction partner can influence the other spatially via spatial prompts, e.g. by saying: "you are too close to me please move on." Green and Hüttenrauch [2006] suggest that a robot should prompt a user to position herself / himself in a better way for interaction. Green [2009, p.177] defines

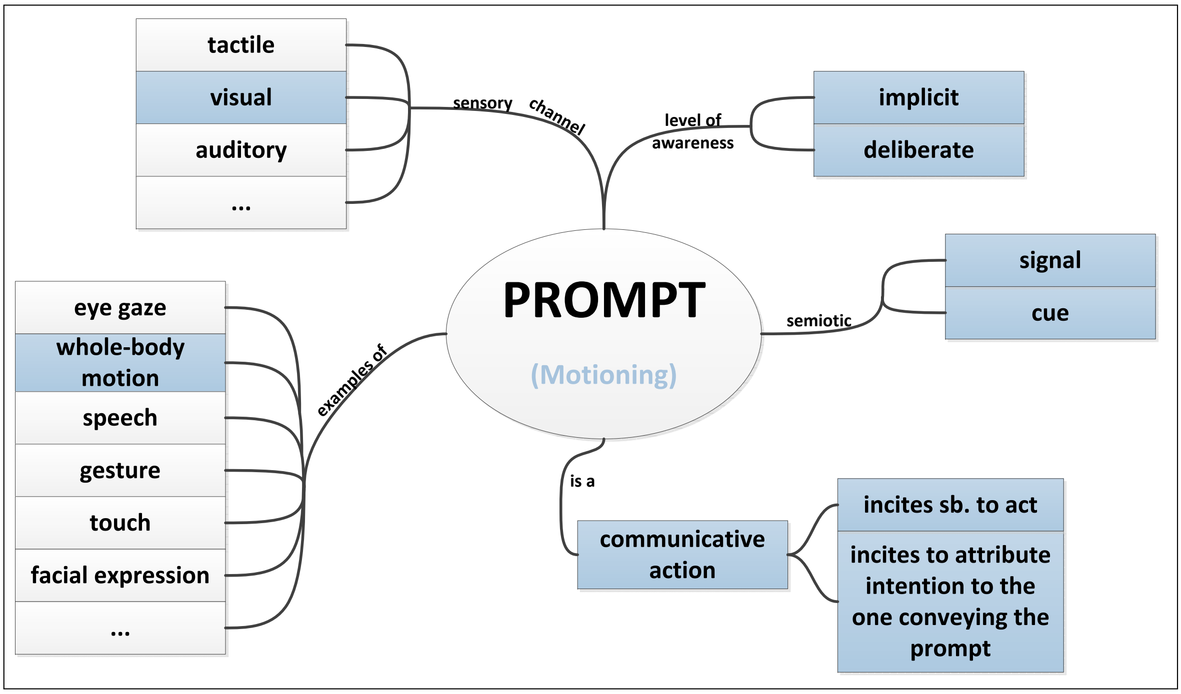

Figure 2.2: *The diagram depicts an overview of the general concept of prompting as Green [2009] defines it. Motionings, which are defined in Section 2.6, have some characteristics in common, because they are a special case of prompts. The boxes which motionings and prompts have in common are marked in blue. For example, motionings are perceived via visual channels and conveyed as whole-body motion. Figure 3.7 (p.71) depicts motionings on a detailed level.*

"a spatial prompt is a communicative action that incites someone to spatial action or to communicative action".

Spatial prompts can be conveyed via eye gazes, gestures, facial expressions or motions with the entire body. These spatial prompts are conveyed to incite an interaction partner to act.

Figure 2.2 serves as an overview of prompts and their characteristics, definitions, and sensory channels and the way prompts occur. However, this will be refined in the next section.

Other signals or cues can also prompt someone to do something. A noise can prompt someone to look for where it comes from. A red traffic light prompts the driver to stop the car. The verbal command "stop" prompts another person to halt. The definition of spatial prompts is taken as a basis for this thesis but needs to be limited for the scope of this thesis as only spatial prompts are considered which are conveyed via whole-body motions as means for spatial coordination or nonverbal communication.

2.6 Preliminary Definition of Motionings

In the previous section spatial prompts were defined. Green's definition of spatially prompting is a very broad one. However, important for this work is only the motion of the body. Physical action in terms of whole-body motion can reveal certain information about the interaction partner's intention, which can be interpreted and the information gained used to spatially coordinate. The term spatial prompting means to incite someone to do something by whatsoever means Green [2009]. As prompting by definition is too general for the purpose of this thesis, a new hyponym is defined: *motioning*. Regarding the axiom of Watzlawick et al. [1967], any action, communicative or not, words or motion, cannot not communicate. This means action also always includes communication. Green's definition is fundamental for this thesis because it provides a first limitation of a kind of communication, namely spatial prompting, but it needs to be limited to communicative whole-body motions for the scope of this thesis.

To emphasise that *the focus lies on communicative motions with the entire body, which incite an interaction partner to a spatial action or communicative action*, a new term is defined and used throughout this thesis: **motioning** instead of prompting. 'To motion somebody' is a hyponym of 'to prompt somebody'. ***To motion somebody is an act of communication via motion with the entire body to incite someone to a communicative action or spatial action***. The noun for this is called motioning. According to the American Heritage© Dictionary of the English Language [1992], the verb *to motion somebody* means: To direct by making a gesture or to signal by making a gesture. In this case a gesture means a whole-body motion. The word "gesture" theoretically denotes any bodily expression [Knapp and Hall, 2009; Breazeal et al., 2005], for this thesis I refrain from using the term "gesture" or "body gesture". The term gesture is often associated with movements with hands and arms, e.g. pointing gestures [Kendon, 2004] which a whole-body motion or a motion with the entire body should not be associated with. Motioning and communication via body motion are treated as synonyms throughout this thesis. Furthermore, body motion, whole-body motion and motions with the entire body are also synonyms. Motioning is the noun in singular form and the plural form is called motionings. The substantive 'motion' for "to motion sb." would be too general.
A motioning describes the act of motioning somebody which is equivalent to the act of inciting someone via whole-body motion. Motionings are considered

in the light of spatial coordination. Humans coordinate each other spatially or manage interpersonal space via whole-body motions. In this case, whole-body motions are conveyed and interpreted to communicate and predict each other's internal goals or intentions and to be able to act accordingly. Motionings that incite someone to an action are a means of body language that contributes to the spatial coordination between people. In the light of this definition the communicative potential of whole-body motions are investigated. First of all robotic whole-body motion patterns in HRI are investigated to survey the human ability to interpret motions and to get ideas how to research motionings that are communicative spatial prompts with the entire body and which help to communicate messages that are important for spatial coordination. Secondly, human motionings in HRI are investigated.

2.6.1 First Indication on Motionings in HRI

The working assumption that motionings exist in HRI is supported by Hüttenrauch et al. [2006b] who report on, small whole-body motions from humans towards a robot and suggest that these have a communicative purpose. Hüttenrauch et al. [2006b] observed that their participants in an HRI study were displaying small body motions between two interaction episodes (following the robot and showing items to the robot). They called the episode between two tasks a transition episode. In this episode, the authors found that humans displayed small steps which decreased or increased the distance to the robot by approximately 15 cm. Moreover, Hüttenrauch et al. [2006b] reported that their participants conveyed also slight posture changes away or to the robot. They called these motions *adjustments* or *preparatory motions* for the action. A summarising visualisation of motionings is displayed at the end of Chapter 3 in Section 3.7. Furthermore, throughout Chapter 3 more cross-disciplinary related information on spatial coordination via whole-body motions is presented. Therefore, Figure 3.7 (p.71) provides a summarising overview of a motioning, its potential characteristics, characteristic values, and its definition. As the title of this subsection indicates: the definition of motionings is *preliminary* because in the course of reviewing the cross-disciplinary related work (Chapter 3) the definition is enriched with more information and more importantly within the investigations of the expression of human motionings (Chapter 6) motionings are precisely described so that other researchers are able to identify motionings in HRI (spatial coordination situations) as well.

Action Segmentation Having defined that a motioning is a whole-body motion over a distinct time, the question arises - when does it start and when does it end? Identifying the beginning and the end of motions or action is important as Brand et al. [2002, p.72] state: “We [humans] detect relevant structure within the flow of motion, note where one action ends and where the next begins, and identify the psychological forces motivating the actor’s specific patterns of movement.” The research area of the action segmentation answers the question of how to define the beginnings and the ends of action intervals: Pauses in the respective action or modality are used as an indication for segmentation [Schillingmann et al., 2009; Peters, 2008]. Consequently a motioning should be also flanked by preceding and succeeding pauses in motion. Furthermore, small pauses are also believed to evoke attention, e.g., hesitation gestures (arm and hand gestures). Hesitations that are micro stops in motion always appear abrupt [Moon et al., 2011]. And in addition, Riek et al. [2010] found that abrupt hand and arm gestures communicate more quickly than smooth ones. The authors assume that abrupt motions convey a sense of urgency which lets people react quicker, in particular, when abruptness is achieved with high contrasting velocities of motion, e.g. no motion, quick motion and slow motion. Ogai and Ikegami [2008] and Moon et al. [2011] define a hesitation as stutter in action which can be observed as jerky motion in humans. Hesitation in an action is believed to draw attention to the action, and emphasise the own action, especially in turn-taking situations, e.g., a pointing gesture which is stopped in the middle and continued afterwards, to show something despite a different ongoing conversation [Thórisson, 2002]. Moreover, Van De Weghe et al. [2005] state that humans perceive motion in a rectangular qualitative and relative way, namely, “left-right” motion and “toward-away” motion from their own perspective. A change of direction on either of those two dimensions results in a theoretical small pause in motion. Therefore, I define a motioning as continuously conducted whole-body motion over a distinct time without a pause in motion. Starts or ends of a motioning are defined as: a) an absolute pause in the motion, or b) an abrupt change in direction of motion, or change of orientation of the body or c) a hesitation with micro version of a) and b).

In this sense, an example of a human motioning could be a single step towards a person, which urges the other person to step back. The whole-body motion, a step towards a person, incites the other to step back.

2.7 Natural Behaviour vs. Implicit Behaviour

In Chapter 1 the goal and requirements of this thesis' investigations are introduced. The main requirement for investigating communicative whole-body motion is that the human interpretation and also the human expression of whole-body motions should be performed in a 'natural' way. As Kanda [2010, p.44] reported [a lot of HRI studies using the robot as physical entity] " [...] have revealed the importance of a robot's non-verbal behaviour.[...].These findings are devoted to make interaction with robots as natural as the interaction among humans, i.e., natural-HRI." This thesis transfers this goal not only on the robotic role of the interaction but also regards natural HRI from the human perspective to the robot. That means to observe natural behaviour in humans, humans should not need to learn or practise a new body language. Neither the experimenters of the conducted studies are allowed to help with, nor instruct the participant about body language. Also participants of the studies are not allowed to be informed about the goals of the study. These precautions guarantee that natural human behaviour can be investigated, at least for the situation of interest.

While natural behaviour can be guaranteed by the study settings, the results of this thesis cannot make a statement about implicit communication. Breazeal et al. [2005, p.708] define " [...] implicit communication as conveying information that inherent in behavior but which is not deliberately communicated." While there are physical methods to measure implicit internal human processes (pupils dilatation, heart rate, skin conductance) [Tressoldi et al., 2011] the investigations throughout this thesis do not consider them. This thesis focuses only on nonverbal and natural behaviour which does not need to differentiate between deliberate and implicit behaviour because the important requirement for investigating the communicative potential of whole-body motions in the frame of spatial coordination is that whole-body motions express the internal goals of an interaction partner and that these are interpreted. Breazeal et al. [2005, p.708] states within that topic that " [i]t is well known that observable behavior can communicate the internal mental states of the individual." Moreover, Mutlu et al. [2009, p.69] state that " [i]n interpreting others' feelings and intentions, we rely not only on explicit and deliberate communicative acts, but also on implicit, seemingly automatic, and unconscious nonverbal cues." These internal states can also provide information about the internal goal or intention or social convention behind the behaviour. Finding this message and interpreting it is an important piece of information for a robot, it helps it to determine what behaviour is appropriate and how to act accordingly. For example, a person who steps back from another person could signal that a special interpersonal distance needs to be kept, and the step back could be an invitation for the interacting partner to pass by as there is more room. In this way the whole-body motion can be seen as reference to an internal plan or an intention or convention of how to pass each other. Motionings, for example, are a physical behaviour which is used in interaction to infer the interaction partner's intention. Figuring out the intention behind a motioning is essential for predicting the next actions.

2.7.1 Semiotics

In the semiotic sense a communicative whole-body motion (and a motioning) can be a cue or a signal. A signal is any sign which is explicitly conveyed to alter someone's behaviour. The signal turns into a cue when it is implicitly conveyed, cf. [Hegel et al., 2011]. Analogous to human communication in Watzlawick et al. [1967], robots cannot not convey cues cf. [Hegel et al., 2011]. That means robot motion communicates whether or not it is designed to communicate and therefore it should be investigated to what extent robotic motion patterns are interpreted (cf. Q1 in Section 1.2 and also Chapter 5).

2.8 Spatial Coordination in Narrow Passages via Motionings

As introduced in the illustrative story, blocking situations in narrow passages are in the focus of this thesis, cf. Section 1.1. Narrow passages occur several times in people's homes caused by furniture or other people or robots. Hüttenrauch et al. [2009] brought the mechanoid robot, Minnie, to people's houses and flats and observed several narrow passages in each home. In these narrow passages the human came close to the robot, because the robot was accidentally blocking the way. The robot was not aware of the fact that it blocked the way for the human who was guiding Minnie around the home. In these narrow passages it is crucial to spatially coordinate with each other in order not to crash into each other. That is why communicative whole-body motion as means of spatial coordination in narrow passages are the focus of this thesis. As Hüttenrauch et al. [2009] reported, the robot might from time to time block the path for humans to proceed. In those situations the human needs to negotiate somehow with the robot how to pass by. This situation is the essence of this thesis: a blocking robot in a narrow passage. The authors also reported also that their participants conducted “security breaches” meaning they squeezed around the robot to proceed their way. The relevant questions for this thesis are, in particular, the investigation of human motioning (cf. Q2 and Chapter 6) and is there any indication of spatial coordination via whole-body motions before they squeezed around the robot that the robot did not detect / interpret? This situation is important to be subject of investigations because humans should not need to squeeze around future robots (as they did in [Hüttenrauch et al., 2009]), applied as service robots in human robot-shared environments.

2.9 Summary

To sum up, this chapter limits and defines the scope of this thesis to direct and intimate HRI, meaning that the interaction partners, human and robot, are physically embodied and present in a shared space. The approach is human- and robot-centred so that not only the comfort of the person but also the liveliness of the robot are important within the investigations of this thesis. Moreover, mechanoid and wheeled robots are used and presented to participants as service robots that work in an office environment. The object or phenomena of the study are communicative whole-body motions that contribute to the ability to spatially coordinate with each other in a natural way. The expression and interpretation of communicative whole-body motions appertain to the spatial coordination. Communicative whole-body motions that insight people to a spatial or communicative (or both) actions are suggested to be used in HRI and are observed between interaction episodes from a human with a robot. The term *motioning* is coined for such human communicative whole-body motions (motion with entire body) that are conveyed to spatially influence interaction partners. Crucial situations for spatial coordination are narrow passages in which people, or in this case a human and a robot share space during an interaction (an interaction could also be a short interaction such has passing by or a long interaction such as guiding around to present rooms or items). The initial situation of interest, which is the basis to investigations within the thesis' scope, is the situation in which a robot is accidentally blocking the path in a narrow passage for a human. This situation is reported to happen in HRI situations performed outside the lab and inside people's homes [Hüttenrauch et al., 2009].

2.9.1 Conclusion

This situation is important and should be subject of investigations because humans should not need to squeeze around future robots, applied as service robots in human robot-shared environments. These robots should detect and interpret human motionings but should also communicate via motion. The goal to investigate the communicative potential of whole-body motions in HRI is also an investigation of another piece of human nonverbal communication, namely, spatial coordination that is used on a daily basis in human interactions [e.g. passing each other Patterson et al., 2002] and should be used in HRI also. A blocking situation is a specific HRI situation. It is crucial to spatially coordinate with each other in narrow passages in order not to crash into each other or squeeze around each other. The blocking robot in a narrow passage presents the reason for the human to spatially coordinate with the robot. Spatial coordination includes predicting (interpreting) and conveying whole-body motions. Therefore, the next chapter presents related work within a broad context of spatial coordination, namely, the prediction, interpretation of motion and the expression of motion. Another aspect, interpersonal zones as social conventions, is described. Spatial coordination is achieved by increasing and decreasing interpersonal distance because each interpersonal zone has a different social meaning.

Chapter 3

Cross-Disciplinary Related Work

In this chapter, it is illustrated that motion, as such, is already a powerful tool to communicate social statuses. Motion conveys information about internal goals or intentions or situations, so that people are able to predict next actions. Interpretation, prediction, foreknowledge or tacit knowing enables humans to structure interaction as they foresee the goal of the interaction partner. Furthermore, when motion as communicative tool is combined with the knowledge of proxemics, especially personal zones, it becomes a powerful tool to anticipate next actions of an interaction partner.

On a daily basis, people have to coordinate their whole-body with other people in different environments. Moving and stable obstacles as well as moving and motionless humans are encountered. These factors create the need for the human to predict other people's paths and their intentions in order to safely move from one place to another [Frith and Frith, 2006]. In order to *share space with others in narrow environments*, anticipating the other's next action and acting in time is crucial e.g. when crossing streets together [Ducourant et al., 2005]. Sharing space means also to manage interpersonal space or to coordinate each other spatially. In order to spatially coordinate, means of body language, such as, whole-body motions are interpreted and conveyed. Social conventions such as interpersonal distances help to coordinate spatially by increasing or decreasing interpersonal distances. This ability seems to be anchored deeply within the human nature, as neuroscientific findings state that similar brain areas are active when rating social distances and interpreting social intent [Kennedy et al., 2009].

Within this context a range of related work from research fields of human interaction, human-robot interaction, and the fields of animation and theatre are described and discussed.

Outline of this Chapter This chapter is divided into six sections

- *Interpretation of Abstract Motion:* This section reports on the ability to interpret motion of abstract entities such as triangles and points representing human movement. Furthermore Gestalt principles provide an overview of the human manner of interpreting abstract motion. Neuroscientific findings report on brain areas activating when the humans are inferring intention from motion and mental states of others. In addition, the ability to interpret motion which is deeply imprinted within humans is outlined and examples of interpretation of very abstract motion in the field of HRI are presented.
- *Interpretation of Goal-Directed Motion:* This section defines goal-directed motion and provides examples of the interpretation of goal-directed motion in HHI and HRI.
- *Expression of Motion:* This section draws information from a related field of research, animation movies and how to express motions that appears self-generated and provides the possibility for the audience to anticipate the motion of the designed characters. Furthermore, this section reports on an example transferring animation principles to HRI.
- *Representing Entities in Motion through Characteristics:* This section provides an overview of some characteristics of whole-body motion that are relevant for describing communicative whole-body motions and reports on an example how to represent motions of two entities in space.
- *Interpersonal Distances:* This section provides an overview of a characteristic of motion, change in distance. Changing the interpersonal distance has an effect on the spatial coordination of people because different interpersonal distances have different social meanings. These not consciously perceived social conventions influence people in the way they feel and act. Moreover, regarding the activation of brain areas, neuroscientific findings suppose an interplay between sensing different distances and inferring an intention from motion.

- *Spatial Coordination via Interpersonal Distances in HRI:* This section provides an overview of the HRI studies that measure the human minimal comfortable distance from a robot.
- *Summary:* This section provides a summary of this chapter and provides a figure that summarises information on motioning to bear in mind, especially, for Chapter 6.

3.1 Interpretation of Abstract Motion

This section reports on the human ability to interpret motion of abstract entities such as triangles and points on a screen that represent human movement. Early work is conducted by Heider and Simmel [1944, p.243] as they wanted to find out "what features of the situation are of importance or how the situation influences the perception". They found that their results related to certain rules that stated how humans interpret things – the Gestalt principles. Later, Heider [1958] supposed that there is a connection between biological motion perception and social cognition that can also be summarised by certain rules similar to the Gestalt principles. Moreover, neuroscientific findings provide a connection between motion perception and social inferences. These findings report that the same brain areas in humans are activated when inferring intention from motion and mental states of others. Furthermore, the same researchers argued that the ability to interpret motion is favoured by the evolution, because it is a fast way to predict the enemies' next actions. Moreover, this section presents an example of currently conducted studies within the topic of abstract motion interpretation in the field of HRI.

3.1.1 Early Work by Heider and Simmel

Heider and Simmel [1944] published a study in which they showed that the motion of 2D objects (outlines of circles and triangles) together on a white background provides enough information for humans to attribute character, motive and intention to these objects cf. Figure 3.1. Heider and Simmel's work from 1944 is taken as an inspiring example that characteristics of motion are a powerful communicator of intent that should be considered in HRI. In their study, 34 participants had to watch a film[1] with these simple geometric objects moving around. Afterwards, they had to narrate what they had seen. All participants considered these objects as animate creatures and ascribed a motive to them. Heider and Simmel [1944, p.234] wanted to find "important features of the situation" with this approach. They identified *temporal succession* and *spatial proximity* of the objects as important principles when interpreting the motion of objects cf. Figure 3.1 for spatial proximity. Moreover, speed of moving objects was also considered to be a salient feature upon which the coherence of two events is assumed. Key interpretation of the data was that participants treated spatial and temporal correlation as a reason to build a causal chain and attribute social roles to the triangles and the circle. In addition, they identified that the attribution of social roles depends on which object the participant saw moving first, e.g., the circle chases the triangle vs. the triangle is leading the circle. Transferring this knowledge to HRI: timing of robot motion in relation to the human interaction partner's action becomes very crucial, meaning that the interaction partner might associate the robot motion with the own action which was conveyed closer in time to the motion of the robot.

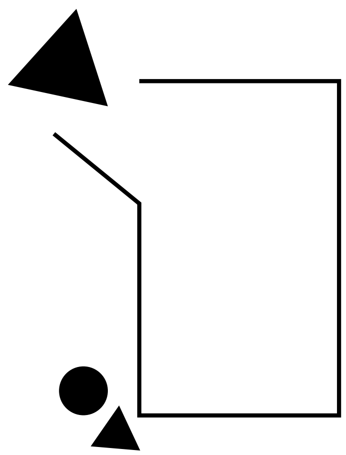

Figure 3.1: *This figure displays a sketch[2] of Heider and Simmel's video study. Participants watched a video clip with moving triangles and a moving circle. They attributed social intent to the three objects, e.g., the big triangle is looking for the small triangle but the little triangle runs away with the circle. The circle and the small triangle are friends (spatial proximity). Similar stories to this invented one were told. It is remarkable that throughout the participants similar stories were told, so that the motion of the objects was interpretable in only one way.*

[1] Original clip used by Heider and Simmel in their study in 1944. Last retrieved 20.08.2012: `www.psychexchange.co.uk/videos/view/20452/` and `www.youtube.com/watch?v=sZBKer6PMtM`

[2] This sketch is loosely based on the video clip from Heider's and Simmel's [1944] study.

These findings correspond to certain rules of that psychologists collected to summarise the manner of human interpretation of all kinds sensory input which humans perceive and interpret. This is called perceptual causality; the rules or laws are called Gestalt principles, e.g. humans often assume that successive events are cause and effect of each other. Furthermore humans are interpreting objects that are close together as some kind of connected.

3.1.2 Perceptual Causality: Gestalt Theory

The term Gestalt refers to theories of visual perception developed by German psychologists in the 1920s (Berlin School). These theories attempt to describe how people tend to organize visual elements into groups and build causal chains out of these groupings. These phenomena were grouped by various psychologists under the name of perceptual causality and Gestalt principles. Early findings of these phenomena of perceptual causality were reported by Mach 1870, von Ehrenfels 1890 [Ertel and Metzger, 1975]. Later, the Gestalt theory formed a part of the psychology, established by Wertheimer, Köhler, Kofka and Metzger cf. [reported in Ertel and Metzger, 1975; Katz and Metzger, 1969; Frisby and Stone, 2010]. The Gestalt principles assemble laws of perceptual organisation. For example, objects of similar size can be seen as a whole and as a new object. One of the main statements of Gestalt principles is that "the whole is different from the sum of its parts". Single parts can form something new and different. A group of similar objects can be interpreted as a new object and cannot be recognised when some of the objects are missing. For example a number of circles are arranged close together that humans perceive a square (spatial proximity) and not a single circle cf. Figure 3.2.

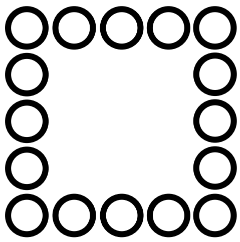

Figure 3.2: *This figure displays a simple example*[3] *of the Gestalt principle* `proximity`. *A number of circles are arranged in a way that people perceive a square which cannot be reassembled by only one of the circles.*

[3]This example is loosely based on different examples provided by Katz and Metzger [1969].

Goldstein [2010] states that the Gestalt theory explains mainly perceptual causality phenomena that are perceived visually and are thought in design classes of e.g. computer interfaces. Katz and Metzger [1969] state that not only still graphics and geometrical objects underlay these perceptual grouping principles, but also moving humans or moving objects underlay these perceptual grouping principles. In addition to spatial proximity and temporal succession, *continuity* is important for this thesis. A simple example for continuity is that a drawn line on paper, which intersects other patterns can be traced through other lines and objects that overlap and block the view on the line cf. Figure 3.3. The continuity Gestalt principle summarises also the phenomena that humans are well able to predict the future path of moving objects cf. [Johansson, 1973].

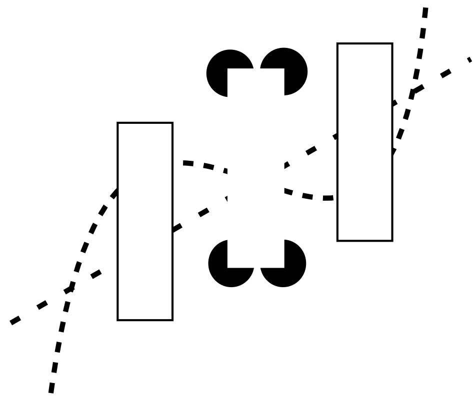

Figure 3.3: *This figure displays examples of the Gestalt principles* `continuity`*,* `proximity`*,* `closure`*, and* `symmetry`*. The dashed lines are recognised as lines because our perceptual system groups similar objects with symmetrical distance (symmetry) and which are close together (proximity) as a whole. The lines can be followed even though they are not continuously visible (continuity). A third rectangle in the middle of the figure can be perceived that covers four circles partly. Even though there are neither circles nor a rectangle, they are perceived as such (closure). The Gestalt principle continuity works also for objects in motion: then, not a static line would be recognised but a moving object and the future path would be predicted and estimated at times the sight is blocked.*

Heider [1958, 1983] drew a first connection between perceptual grouping principles and social cognition. Heider found that the presentation of simple objects in motion elicits high-level social interpretations. Thus the perceptual causality cannot only explain the perception or interpretation of simple geometric objects, but also in social interaction scenarios [Michotte, 1963; Runeson, 1977; Rime et al., 1985; Scholl and Tremoulet, 2000]. Furthermore, Johansson [1973] found that the trajectory estimation of our visual system and the ability to extract motion patterns play a role cf. also

[Frisby and Stone, 2010]. Johansson [1973] reported that their participants in a study were able to group moving white points on a black screen and interpret that these points resembled a human performing different actions. The white points are called 'point light figures' throughout the literature[4]. The insight of the results was taken as means to test the ability of humans to interpret social processes [Pavlova, 2011] and is further explained in the following section.

3.1.3 Neuroscientific Findings

Not only psychologists, but also neuroscientists found a connection between biological motion perception (e.g. walking person) and social cognition (e.g. Theory of Mind[5]) [Pavlova, 2011; Castelli et al., 2000]. Castelli et al. [2000] found that the same brain regions[6] are activated when observing movies of abstract object motion (similar to the ones of Heider and Simmel [1944]) and when watching human body motion or when humans reflect on their own mental states.

Similar to Heider and Simmel's video clips, Castelli et al. [2000] showed videos of moving geometrical objects (triangles) to their participants, who interpreted that one of the triangles was surprised or mocked, persuaded or deceived the other. In these animations, participants were expected to and did attribute a Theory of Mind (ToM) to the triangles. Watching these animations elicited a high activation in regions which were also activated when people make inferences about other people's mental states (i.e. if they have a ToM of others).

Pavlova [2011, p.1] states that "visual processing of biological motion (BM) produced by living organisms is of immense value for successful daily-life activities and, in particular, for adaptive social behaviour and nonverbal communication". Pavlova [2011] found that people, who are preterm neonates or individuals with autistic spectrum disorders or people with genetic developmental conditions. In short, people who have problems managing their daily social lives, were not able to interpret or had difficulties

[4]This white point figures are called point light figures because first studies presented video clips in which lights were attached to human joints and were filmed in the dark without any other light cf. [Goldstein, 2010]

[5]Having a "Theory of Mind" means basically being able to make inferences about other people's mental states.

[6]These brain regions are the medial frontal region with the medial prefrontal cortex and the cingulate cortex. These brain areas are activated by all kinds of task which require the ability to attribute mental states to others cf. [Castelli et al., 2000].

interpreting motion patterns of point light figures dancing, running or displaying sad emotions. Contrary to healthy humans, they were able to make out distinct motion patterns in moving clustered points and attribute social roles and intents to them. Moreover, Pavlova [2011] found that the perception of biological motion and social cognition have overlapping activated brain areas and share some neural circuits.

3.1.4 Judging Intention from Motion is Deeply Imprinted

Barrett et al. [2005] argue, from an evolutionary point of view, that the ability to perceive whole-body motions is a fast way to judge someone's intention, even if no other cues are available, e.g., the silhouette of a person in the dark. Quick judgement of motions may save a person from dangerous situations. As Scholl and Tremoulet [2000] argues, this sort of judgement is a result of evolution. For example judging the intention from a fast and towards oneself moving creature saves not only animals but also humans from dangerous situations, cf. [Barrett et al., 2005]. Castelli et al. [2000] found that participants, who had been told that they were going to see an abstract animations of triangles with thoughts and feelings in it and participants, who had been given no explanation for the animations, told similar stories about the moving geometric objects (similar to Heider and Simmel [1944]). Castelli et al. [2000] suggested that this result shows how deeply ability to interpret motion is imprinted in us. Scholl and Tremoulet [2000] believe that the visual system may infer missing information about physical appearance of object, e.g. hidden edges of a triangle. The ability to add missing pieces in the visual system is built on interpreted information and social knowledge.

3.1.5 Abstract Motion in HRI

Abstract motion is a very powerful means of nonverbal communication, which should be explicitly used in HRI. An example for very abstract motion in HRI was created by Harris and Sharlin [2011], who explored the affect in interaction with a very abstract robot "the Stem". The Stem is nothing more than a 1 metre long, square and wooden stick which is able to roll, tilt and yaw at different speeds. Harris and Sharlin [2011] found indications that even this unfamiliar- and unnatural-looking robot was able to elicit interpretations of inner states of itself. Participants interpreted and attributed emotional states (happy to aggressive) to the Stem in interaction situations, in which the robot displayed motion patterns initiated by a human wizard, e.g. moving up and fast to one side.

Abstract motion not only conveys emotional states, but in particular whole-body motions can reveal intentions from interaction partners. Mutlu et al. [2006] designed an abstract social interface to examine the minimal use of cues such as motion. The social interface consisted of a projected star (flower-like figure) on a wall at their university foyer. The figure moved parts of its body to correspond to different types of social interaction in its vicinity. Even though this interface had no special intention to convey, and as a whole it was unable to move in any direction, frequent passersby attributed inner states like happiness and curiosity to different appearances of the projected figure on the wall.

To sum up, subtle features of a body in motion, such as change in position, posture, speed and temporal succession of body motions, and proximity to others are sufficient to convey information about a situation. Recognising biological motion and the intention behind that particular motion is crucial for coping with daily social tasks, in particular at the interpersonal level. Moreover, recently researchers provided evidence that very abstract robots and animations projected on a wall are attributed to have emotions.

3.2 Interpretation of Goal-Directed Motion

This section explains that the motion from which an intention should be interpreted should be goal-directed, otherwise it is ambiguous and might not be interpreted the right way. An action needs to be goal-directed to be able to interpret the intention behind the action [Tomasello et al., 2005]. In order to do that, Tomasello et al. [2005] emphasises that there are always two roles or dimensions in interaction which each interacting partner takes.

1. *The interpreting role* includes anticipating or predicting each other's intention and goals.
2. *The conveying role* includes conveying a goal-directed action, which helps others to anticipate the next action and in turn helps the one, who conveys the action to reach or fulfil her / his goal.

A goal-directed action can be spontaneously performed to implicitly communicate an intention. An intention includes a goal or a plan of an action that someone chooses to follow [Tomasello et al., 2005].

The plan of an action can also include subgoals. They are lower level goals, which are necessary to fulfil or reach the desired state, Tomasello et al. [2005]. The action or body motion by itself is ambiguous without a goal, e.g. a straight movement towards somebody could mean somebody wants to hit, kiss, speak to or pass by the other one. *The question, which arises for the scope of this thesis, is by which characteristics of whole-body motion is the intention made transparent* cf. Q1 and Q2 Section 1.2. Q1 asks this question with respect to robot motion, and Q2 asks this question with respect to human motion.

Transferring, that motion needs to be goal-directed to be interpreted, as requirement for motionings – a motioning needs to be a goal-directed action. This means that in situations, in which motionings occur, people should have a specific goal in mind. It is expected that in situations, in which people actually have the intention to reach a physical desired location (a place in a room), motionings occur, from which the goal or intention is inferable. Tomasello et al. [2005] states that the physically desired state motivates intrinsically to take action, plan how to reach the physical goal, and solve problems (form subgoals), which occur on the way.

The process of predicting an action and interpreting a goal-directed action are inseparable in literature, and authors have invented different names for it. For example Kirby [2010] calls the knowledge, which is acquired while interpreting actions: *foreknowledge*. Similarly, Gill [2004] uses the term *tacit knowledge* and Sebanz and Shiffrar [2009] describe it as *anticipation and prediction*. Barrett et al. [2005] calls it *inferring and judging intention*.

3.2.1 Examples of the Prediction of Goal-Directed Motion

Another important aspect of interaction is the predictability of the partner's action. Frith and Frith [2006] found that humans can infer intentions from another person's movement. Human research provides information on how people are able to predict what other people are going to do, only by watching the other person's movement [Frith and Frith, 2006; Sebanz et al., 2006; Obhi and Sebanz, 2011]. Among others, this information is encoded within the body motion. In addition, conversation analysts found posture changes and position changes that influence conversations [Kendon, 1990]. Sebanz and Shiffrar [2009] examined, how well experts could predict basketball players faking a pass or actually passing the ball. They presented point light figures of players to expert participants. These experts predicted significantly above chance the intention of the basketball players. This shows that people are well able to use dynamic characteristics of goal-directed motion to infer other's intention.

3.2.2 A Technical System Infers Intention from Motions

Crick et al. [2007, p.138] state that humans are able to create consistent interpretations from incomplete data, "as long as they have motion cues to work from". Therefore, their goal is to use characteristics of motion only in their system. Crick et al. [2007] also criticise that there is a difference between interpreting intentions from designed moving objects (e.g. video clips designed in the style of Heider and Simmel [1944] or Barrett et al. [2005]) and motion of human interactions. Therefore, Crick et al. [2007] set up a ubiquitous human and object tracking system to track participants playing a game of tag, and to be able collect real world interaction data. The tracking data was used to build animated squares representing the participants. Human coders, watching the abstracted version of the game of tag, were able to identify whose turn it was to tag, i.e., to recognise whose intention it was to catch the others. Crick et al. [2007] had the idea to build a system that could infer this information from the motion. Their general idea was to represent each agent or object as a force vector. Each vector was also subject to other repulsive and attractive force vectors, so that "the object's acceleration is the sum of the attractive and repulsive vectors associated with each of the other agents/objects in the scenario" [Crick et al., 2007, p.136]. The algorithm estimates the best fit hypotheses plus three different weights to represent the influences between the agents. [Crick et al., 2007] claim that their system is nearly as good as a human annotator inferring the object's intention from their motion online. Two human annotators agreed on 78.5% of the cases when judging the players whose turn it was to tag, whereas a human annotator and the system agreed on 70.8% of the cases. Limitation, however, is that the system knew what game was being played. This means that the system is only able to infer motions with the knowledge about the situation which is to be interpreted. The system is not yet able to interpret any goal-directed whole-body motion. The system was able to infer, from the force vectors, two spatial relations between the geometrical objects in the above example, e.g., object 1 is approaching object 2 and 3. Object 2 and 3 are avoiding object 1. These robotic interpretations are only similar to human interpretations when considering a simple game of tag, but this cannot be generalised to other human interpretations of other situations.

To sum up, this section explains that internal goals or intentions of people can be inferred by watching the whole-body motion of humans. This means, for the investigation within the scope of this thesis that any conveyed robotic whole-body motion needs to be some kind of goal-directed to enable participants to interpret robotic whole-body motion. Furthermore, human motionings are expected to occur whenever humans have an internal goal which is especially visible when humans have a physical goal to reach.

A related field of research, animation of characters, provides insight of how communicative whole-body motions should be designed and when motionings could occur.

3.3 Expression of Motion

The idea of using body motion as carrier for intention and emotion is not a new idea in the entertainment industry, in particular, when animating cartoons. Disney (founded in 1970) and Pixar (founded in 1986) have had several years of expertise in animating cartoons, [Lasseter, 1987; Thomas and Johnston, 1995].

Experts of animation films (e.g. Disney Studios and Pixar Animation Studios) found that animated characters in films appear livelier when the audience is able to predict the next actions, emotions and intentions of the animated characters. From experience (trial-and-error method) they developed animation principles as guidelines how to design characters cf. [Thomas and Johnston, 1995; Lasseter, 1987]. These have also found their way into HRI research and provide a basis from which the design of robot behaviour can learn from cf. [Takayama et al., 2011].

3.3.1 Prediction of Action - Animation Principles

Not only spatial proximity and speed of animated objects and temporal succession of motions are important to convey intention cf. Gestalt principles 3.1.2. Thomas and Johnston [1995] (Disney Studios) and later Lasseter [1987] (Pixar Animation Studios) presented animation principles which explain how to make animated characters appear lively.

For this thesis the most important animation principles are explained in the following text: One of the principles is called *anticipation*. It explains how to make the thoughts of a character about an action visible, so that it appears as if the character thinks and acts on its own. Small movements shortly before the actual action is performed should communicate information about the action, e.g. little steps towards a goal before running there, rubbing hands or licking lips before eating something nice. These movements need to be somewhat goal-directed to convey the intention, for example, orienting towards an item, subtle motions towards something, eye gazes to and away from something, could convey the intention that the character wants to eat or reach or have an item [Thomas and Johnston, 1995]. These motions somehow provide the information to enable humans to anticipate the action and infer the intention [Thomas and Johnston, 1995; Lasseter, 1987]. Related to the anticipation principle is the *principle of timing*, which is similar to the Gestalt principle of temporal succession. Actions, which follow each other closely in time, are easily interpreted as connected events. Subtle movements, conveying intentions, need to be at the right time before the actual action takes place. This allows a character to appear lively because the audience can predict its intention and attributes a self-generated behaviour or thinking to the animated character [Thomas and Johnston, 1995; Lasseter, 1987].

Zacks [2004] found supporting evidence that people use these indications of the action to predict the next action. In a study Zacks [2004] found that participants annotate beginnings of actions right before the actual movement of an action begins. Participants of their study not only use but also think that the cues, which give information about the action before the actual motion starts, belong to the action itself, e.g., vibrating ground in a subway tunnel is a cue for the advancing train even if that subway is nowhere to be seen.

Other animation principles, which are also well known in theatre, are *exaggeration* [Thomas and Johnston, 1995]. In small doses exaggeration of motions is used to generate legible messages for the audience, e.g. repetitions of motions, such as, licking lips twice, abrupt motions, such as fast motions, pauses in motion, repeating single steps back and forth before a mouse starts running to a cheese cf. [Thomas and Johnston, 1995; Lasseter, 1987]. Similar to the exaggeration principle is the *intersensory redundancy hypothesis* that states that similar information conveyed over different channels of communication (e.g. visual, auditory) facilitates learning in children as it makes the information more salient and rules out wrong interpretations cf. [Bahrick and Lickliter, 2000]. [Bahrick and Lickliter, 2000] explain that temporal synchronous, redundant and amodal information can also direct attention to meaningful events, which may be beneficial for learning in young infants. This finding is also used in HRI research to inspire approaches how to identify salient information from the constant stream of arbitrary information for robotic systems, cf. [Peters, 2008; Schillingmann et al., 2009]

3.3.2 Animation Principles in HRI

Fairly new is the idea to use motion as a carrier in robots in interaction with humans cf. [Nakata et al., 1998]. Newer is the idea that humans in interaction with robots might show similar behavioural patterns as if they would interact with another human [Hüttenrauch et al., 2006b]. And only recently, animation principles were transferred to the field of HRI and applied at a HRI study conducted by Takayama et al. [2011]. Takayama et al. [2011] state that robots should display forethought to appear lively to humans (forethought is here corresponding to the animation principle of anticipation). Robot forethought means that people attribute to the robot the idea that it has actually thought about an action before performing it cf. [Takayama et al., 2011]. This can be achieved through small movements of the robot, similar to the described animation principles. In a video study, Takayama et al. [2011] found that small movements (orienting, subtle motion backward or forward) before the actual action was performed or before a question was uttered by the robot, helped participants to significantly anticipate the action the robot was engaged in (opening door, requesting power, delivering drinks, ushering a person) more compared with participants who had not seen video clips with these anticipatory motions. Takayama et al. [2011] concludes that these motions can be used when communicating intention or goals of robots.

Corresponding to the fact that anticipatory and subtle motions happen before an actual action is performed, are the findings of Hüttenrauch et al. [2006b]. Hüttenrauch et al. [2006b] observed that their participants displaying small body motions between two interaction episodes (following and showing). They called the episode between two tasks transition episode. In this episode they found small steps, changing the distance towards robot about 15 cm and slight posture changes away or to the robot. They called these motions *adjustments* or *preparatory motions* for the action. These preparatory motions are conforming to the reports on the animation principle, anticipation.

To sum up this section: the essence for this thesis is that actions do not only comprise the actual motion but also motions shorty before. These preceding motions enable people to anticipate the motion. These motions are similar to motionings defined in Section 2.6. Implementing these preparatory or anticipatory motions for robots helps humans attribute self-generated intent to the robot. The perfect timing of successive - or temporal synchronous motion is important to make the motion unambiguous. Making the motion unambiguous increases the legibility of the message behind the motion. Exaggerating or repeating anticipatory motions can increase the legibility of the motion as well. These findings are especially important for the investigations of my thesis as they indicate where human motionings can be expected in the course of a human-robot interaction. It is expected that motionings occur right before an action begins which is supported by the findings of small human preparatory motion in a HRI scenario which Hüttenrauch et al. [2006b] reported cf. Section 2.6.1. Motions that indicate what the next action is going be, are useful in robot interaction as the robot could have enough time to detect and interpret these.

3.4 Representing Entities in Motion through Characteristics

Barrett et al. [2005, p.313] state that *"whole-body motion is a reliable, valid, easily perceived source of information about intentions because different kinds of intentional action have different motion signatures"*. This summarises exactly the motivation for arguing that whole-body motion as communication should be transferred to HRI. Furthermore, Blythe et al. [1999] states that motion signatures of objects and of points representing human joints convey the goals and intention of the interaction partner.

Consequently, the identification, the description, and the representation of characteristics of whole-body motions have been the goal of researchers throughout the cross-disciplinary and for this thesis inspiring fields of research.

3.4.1 The Characteristics Position and Orientation

Barrett et al. [2005] examined six intentional motions to find the cues which characterise the specific intentional motion: a) pursuit/evasion, b) fighting, c) courting/being courted, d) leading/following, e) guarding/invading and f) playing. Participants had to categorize these motions on the basis of an abstracted version of the whole-body motion, namely, by computer animated arrow heads, '$<$'. Prototypical motions with arrow heads were extracted in another study from participants, who had to construct these goal-directed motion patterns in a PC game.

One outcome of the judging study was that 4-year-olds, 5-year-olds and adults from the German population and the Shuar population (people from Ecuador) were able to infer the underlying intention of the motion patterns. Barrett et al. [2005] identified that position and orientation (here the direction of the front of the body in degrees) and their changes are useful in characterising motion patterns. Therefore, Barrett et al. [2005] uses the following characteristics of motion in identifying and categorising the six goal-directed motion patterns:

- absolute mean of each agent's velocity (pixels/second)
- relative velocity of the two agents (pixels/second)
- distance between both agents in (pixels)
- absolute mean of each agent's change in orientation (degrees/second)
- change in orientation between two persons (degrees/second)
- relative orientation of the two agents (degrees)
- relative angle between one agent's orientation and the other's position (degrees)

Having characteristics that describe goal-directed whole-body motion is important for comparing motion patterns throughout different studies. Moreover, it is important for describing and representing whole-body motions for technical systems, such as, robots cf. [Crick et al., 2007]. Therefore the characteristics orientation and positions are considered throughout the investigations within this thesis in particular the investigation of human motionings cf. Chapter 6.

3.4.2 Motion Signatures Reveal Behaviour Patterns for Robots

Not only emotional states or intentions but also entire behavioural patterns can be communicated simply through body motion of a mobile robot. Motion patterns relating to dogs greeting their owner and friends of the owner were transferred to a mechanoid robotic platform, a knee high Pioneer robot, for an HRI study cf. [Syrdal et al., 2010]. The outcome was that even if this robot was not dog-like in appearance, participants in the study thought that the robot reminded them of a pet. They detected behavioural differences of the robot towards its owner and a guest visiting the owner. The speed of approaching and orientation of the camera towards the person plus the way of approaching the humans were altered in the behaviour of the robot toward the owner and the guest. Syrdal et al. [2010] state that these characteristics of motion are the important ones to create communicative motion patterns.

3.4.3 Qualitative Representation of Two Moving Entities in a Relative Framework

Furthermore, the characteristics of whole-body motions can be expressed relative to other entities and in a qualitative way. This idea comes from the field of geography: Van De Weghe et al. [2005] presented a spatio-temporal language for representing and reasoning about movements of entities. This language is based on the "double cross calculus" approach of Zimmermann and Freksa [1996]. They presented an approach to qualitative spatial reasoning based on directional orientation information as available through perception processes or natural language descriptions. The idea to represent moving entities in qualitative way and in relation to other moving entities is motivated by the facts, which Zimmermann and Freksa [1996, p.52] summarised "we known from research in cognitive psychology that humans are poor at estimating angles and make use of rectangular reference systems for spatial orientation", e.g., someone would say "towards", "away from me", "on my left hand side" or "on my right" when describing another person in motion relatively to oneself. Van De Weghe et al. [2005, p.65] calls this the "towards/away-from dichotomy (for the distance constraint) and left/right dichotomy (for the side constraint)". The name double cross comes from drawing these dichotomies for two entities results in one cross for each entity connecting these results in a double cross:"++". In addition, humans would usually not state numbers in measurements like centimetres or degrees: "Spatial reasoning in our every day interaction with the physical world is mostly driven by qualitative abstraction of the (too precise) quantitative space" [from Cohn, Hazafika, 2001 cited in Van de Weghe et al., 2006, p.101]. Moreover, Van de Weghe et al. [2006, p.99] states that "[...] motion is the key notion in our understanding of spatio-temporal relations". Therefore, Van De Weghe et al. [2005] present a qualitative way of describing two disconnected and moving entities relative to each other. In general, this language is called *Qualitative Trajectory Calculus (QTC)*. The QTC is a way to collapse continuous characteristics to qualitative descriptions to take out some of the complexity of continuous data and to be closer to the human description of measurements. Different types of QTC's are defined depending on the level of detail and the number of spatial dimensions. Furthermore, it has been recently shown that *QTC* can be used to represent simple human-robot spatial interactions, like approach behaviours cf. [Bellotto, 2012]. Subsequently, two types of QTC's are presented:

- the basic QTC_B for representing motion of entities by describing the distance between pairs of entities changing over time cf. [Van de Weghe et al., 2006] and
- the QTC_C (QTC - Double Cross) for representing moving entities based on describing their trajectories with respect to each other cf. [Van De Weghe et al., 2005].

The evaluation of this thesis' video data of the HRI studies, is based on the idea of these QTCs cf. in particular Chapter 6: 'Investigating Human Motionings'.

Van de Weghe et al. [2006] suggest to rate the change of motion of an entity in relation to another entity with a set of three categorical values {-,0,+}. In general, this set is used to describe the change in one characteristic (or primitive) for one entity by comparing positions of the two entities at different successive points in time.

QTC_B is presented for one dimension (1D) (QTC_B1D): describing the relative change over time in distance for two entities: The relative change in distance between two entities is annotated with three values: each object can 'move away from (increase the distance (+))' or 'move towards (decreasing distance (-))' the other entity or can be stable with respect to the other ('no change in distance (0)'). These values are obtained for each entity separately: by comparing the distances

for each entity at two successive periods $t^- \prec t^+$ in time with respect to the other entity at the current time point t which lies between the successive periods in time $(t^- \prec t \prec t^+)$[7]. To obtain the value for an entity **k** with respect to an entity **l** one needs to compare:
the `distance` between **l** at the current point in time (t) and **k** during the period (t^-) immediately before the current time point (t)
and
the `distance` between **l** at t and **k** during the period (t^+) immediately after the current time point (t) cf. [Van De Weghe et al., 2005, p.66].

The reason for comparing an interval before and after t is that the motion at time point t needs to be rated, so the motion before and after is studied to be able to make a statement about the time point t, e.g., the value '+' is only rated when the distance increases over the entire time. The mathematical formalism, when to obtain a '+' for entity **k** with respect to the position of entity **l** is presented as follows to illustrate the exact notation[8] [for the entire formalism consult: Van de Weghe et al., 2006, p.104-105]:
+: **k** is moving away from **l** (increasing distance):

$$\exists t_1(t_1 \prec t \wedge \forall t^-(t_1 \prec t^- \prec t \rightarrow d(k|t^-, l|t) < d(k|t, l|t))) \wedge$$
$$\exists t_2(t \prec t_2 \wedge \forall t^+(t \prec t^+ \prec t_2 \rightarrow d(k|t, l|t) < d(k|t^+, l|t))) \quad (3.1)$$

The value for entity **l** with respect to the position of entity **k** at time point (t) is obtained in the same way with **k** and **l** interchanged. This way of rating continuous motion for distance results in nine different combinations for QTC_{B1D}, e.g., '+-' represents: entity **k** increases the distance (+) from the entity **l** (**k** is moving away from **l**), while entity **l** is decreasing the distance (-) from entity **k** (**l** is moving towards **k**). A scene from a chasing scenario could be represented in such a way: entity **l** chases entity **k** cf. [Van de Weghe et al., 2006] and [Van De Weghe et al., 2005]. Figure 3.4 displays a sketch for '+-', consult also the mathematical formalism 3.1 for a precise instruction of how to obtain '+' for **k** with respect to the position of **l** .

[7] $t^- \prec t \prec$ means that t^- is temporally before t.
[8] The notation is defined as follows:
$k|t$ denotes the position of an entity k at time t,
d(v, u) denotes the distance between two positions u and v.

QTC_C **is presented for two-dimensional motion of two entities:** The version of QTC_C is used that considers only the distance and the relative direction of each entity with respect to the other. These two dimensions are derived from the towards/away-from dichotomy and left/right dichotomy (as earlier described). In the same way as Van de Weghe et al. [2006] suggested to only rate the change in distance, Van De Weghe et al. [2005] suggests to rate additionally the left/right dichotomy. The authors suggest to imagine that each entity is standing perpendicularly on a cross with a line RL that connects them cf. Figure 3.5. This cross denotes two dimensions of directions of motion: either to the right-hand side or to the left-hand side of the reference line RL and either towards or away from the other entity's position[9] cf. Figure 3.5. Thus, there are trajectories in two directions [Van De Weghe et al., 2005].

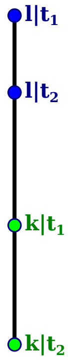

Figure 3.4: *This figure displays two entities (blue, green circle) moving along one dimension at the time points t_1 and t_2:* ***k*** *is moving away from* ***l*** *and* ***l*** *is moving towards* ***k*** *. The QTC_{B1D} notation for this figure is '+-'. This is also explained in the text. The mathematical formalism 3.1 defines how to obtain '+':* ***k*** *is moving away.*

[9] There are also the "0" values, which in both cases denote 'neither right nor left' and 'neither towards nor away' see following definitions.

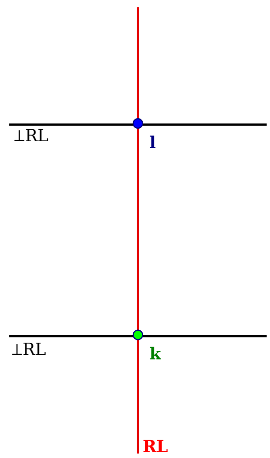

Figure 3.5: *This figure displays the QTC_C Double Cross with the line RL (red line) that connects both entities **k** (green circle) and **l** (blue circle).*

Rating the motion of two entities results in *four qualitative relations* with a set of three values {-,0,+} which are defined as follows:

1. motion of **k** with respect to **l** at time point t (towards/away-from dichotomy)

   -: **k** is moving towards **l**

   0: **k** is stable with respect to **l** (**k** is neither moving towards nor away from **l**)

   +: **k** is moving away from **l**

2. motion of **l** with respect to **k** at time point t (same as in 1., but with **k** and **l** interchanged)

3. motion of **k** with respect to RL at time point t

   -: **k** is moving to the left side of RL

   0: **k** is moving along RL or not moving at all

   +: **k** is moving to the right side of RL

4. motion of **l** with respect to RL at time t (same as 3., but with **k** and **l** interchanged)

The relative motion of two entities at time point t, therefore, can be expressed by a 4-elements state descriptor such as '+0+0': **k** is moving away from **l** (+) while is stable with respect to **l** (0) and **k** is moving to the right side of RL (+), while **l** is not moving at all (0) which means in this case "entity **k** is moving away and to the right-hand side while **l** is standing still". Figure 3.6 displays the Double Cross for this example. The total number of possible 4-elements state descriptors are $3^4 = 81$ [Van De Weghe et al., 2005].

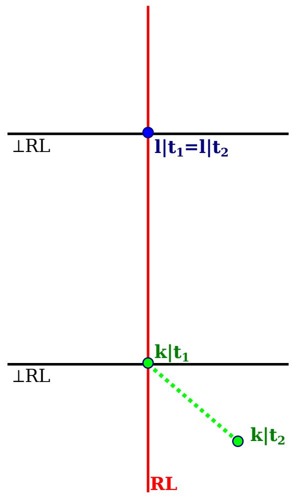

Figure 3.6: *This figure displays the QTC_C Double Cross an example of entity motion '+0+0': entity **k** is moving away (+) and to the right-hand side (+) of the line RL (red line) at time point t_1 to t_2 while **l** is stable in both directions (0) (0). This example is also explained in the text.*

To sum up: the QTC_c was considered as an inspiration basis for the qualitative analysis of the characteristics of motionings as it poses ...
a) ... an advantage to represent information of two moving objects throughout different situations in comparable and mathematically sound way.
b) ... a way to reduce the mass of quantitative data into a qualitative framework
c) ... a basis to represent the whole-body motion patterns that can be detected by a robotic system [Bellotto, 2012].

3.4.4 Short Summary

To summarise this section: characteristics of moving entities should be represented in a qualitative and a relative framework to describe similar to human motions of entities and to cope with the continuous mass of data. The characteristics *orientation*, *position* and *changes* of both characteristics describe different types of whole-body motion. Furthermore, the expression of these characteristics in a relation to an interaction partner and the expression of data in a qualitative framework can summarise data into categorical values and can express data in a way which is more interaction related. Moreover, the characteristics, *direction of motion (trajectory)* and *interpersonal distance*, describe two moving entities in space. These characteristics are considered for the description of human motion within the scope of this thesis, especially in Chapter 6.

3.5 Interpersonal Distances

Humans spatially influence each other via the increase and decrease of their interpersonal distance. Increasing and decreasing the distance is realised by whole-body motions in the form of steps. Even slight decreases of distance between people, especially, when close proximity to each other (< 50 cm) might be tolerated with difficulty, and may lead to feelings of embarrassment cf. [Ducourant et al., 2005, J.N. Bailenson et. al cited in].

The minimal comfortable distance from humans towards a robot is influenced by the general degree of comfort that is felt during the interaction. Consequently, this influences the effect by which an increase or decrease of interpersonal distance has while interpersonally coordinating each other. Neuroscientific findings indicate insight that the ability to interpret motion of other humans, sensing and coping with different interpersonal distances are interlinked. Interpreting the information provided by human body motion is essential in coping with everyday social life, as is the ability to estimate the appropriate distance between oneself and an interaction partner. Hall [1963] coined the term *proxemics* for research in this field of research.

3.5.1 Spatial Influence via Interpersonal Zones

Proxemics pursues answers to questions regarding interpersonal distances. For example, humans use different distances to each other for communication, and how different cultures perceive interpersonal space at different levels of awareness [Hall, 1963, 1968]. Territoriality is another word for the study of interpersonal space and distances between people. In the books “The Silent Language” and “The Hidden Dimension”, and in other articles, Hall states that proxemics is not a language in itself, but has certainly similarities to language cf. [Hall, 1959, 1966]. Hall compares proxemic features with prosodic features of a language, e.g. pitch.

Relevant for this thesis is the part of proxemics which discusses how humans manage distances around themselves within the focus of nonverbal communication. Hall divided the space relevant for interaction around each person into four zones or bubbles or small, protective, invisible spheres (between itself and others). Hall pioneered in naming of these zones. Each zone is influenced by the types of relationships a human may engage in. The zones are based on outcomes of interviews, which were held with intellectual Caucasian Americans. As the boundaries of these zones are dynamic, each zone has an interval and can be divided into a close and a far phase [Hall, 1966]. These boundaries vary dynamically between people. The boundaries are not fixed as many factors can alter them. These factors include personality traits and conventions within a culture and are often culture-wide [Baxter, 1970]. Environmental and situational factors such as white noise, bad illumination, as well as joint tasks and environmental constraints (wide and narrow rooms), can influence these boundaries [Hall, 1966]. Hall [1966, p.116-125] presents three measurements for each zone which denote the boundaries of the close and far phases and are listed below. Measurements are first presented in metres, followed by feet and inches[10].

- Intimate Zone, 0 - 0.15 - 0.46 m (0 - 6 - 18 in.)
- Personal Zone, 0.46 - 0.76 - 1.22 m (1.5 - 2.5 - 4 ft.)
- Social Zone 1.22 - 2.13 - 3.66 m (4 - 7 - 12 ft.)
- Public Zone 3.66 m - 7.62 m - more (12 - 25 - more ft.)

Hall [1966, p.115] states that human “situational personalities” depend on the zone they are in. Thus the proxemic behaviour is dependent on social conventions for a given situation.

Hall [1966, p.116-125] reported different observations for each zone. At an intimate distance, people tend to feel instead of talking. Touching each other is very easy. If there is talking, it is in a quiet voice (whispering). Unwanted violation of this boundary makes people feel uncomfortable.

In the personal zone, people have elbow room, but are still in reach of each other. This zone is used to have private conversation or collaboration with each other. The social zone is the zone used for formal interaction and conversation. The close part is used for collaboration with co-workers.

[10] The original measurements were presented in feet and inches. The measurement in metres has been converted by the author of this thesis

In the public zone, humans do not tend to speak to each other, unless they are addressing an audience [Hall, 1963, 1968].

Moreover, Hall states that the "distance-sensing process occurs outside awareness" [Hall, 1966, p.115]. This means that people do not actively visualise these boundaries at all the time when meeting people. They are somewhat automatically prompted or cued to react, e.g., moving away, if somebody comes too close, who is not supposed to be near.

Following Hall's first acknowledgement of interpersonal zones between humans, further research was carried out in this field. Various researchers identified different arrangements and numbers of zones, as they studied different cultures and ages. All these studies indicate that there is a primary or possessional territory or intimate zone or pericutaneous or peripersonal area, bubble, ellipse or buffer close too, but outside the body, that humans protect or do not like to be invaded unless they have given their permission cf. [Hall, 1966; Lyman and Scott, 1967; Aiello, 1987; Goffman, 1971; Altman, 1975; Werner et al., 1992a,b; Goffman et al., 1997]. Furthermore, the listed authors found that the boundaries of the bubble vary with culture, personality, age, gender, level of acquaintance and situation.

Additionally, the size of personal zones varies with the walking speed of each person or object involved and with the prediction of the trajectories of other people [Gerin-Lajoie et al., 2005, 2006]. The size of the personal zone increases when the interpretation of future directions of other persons and other tasks claim too much attention. That is why Gerin-Lajoie et al. [2005] assume that decreasing walking speed and increasing the size of the personal zone provides a person with more time to plan her / his next actions and predict that of others. In addition, the duration of a boundary breach and whether or not a person is able to predict the end of a boundary breach influences the size of the zones and how comfortable the person feels while enduring the boundary breach, e.g., in elevators people tolerate being close together within a short period of time cf. [Hall, 1966; Goffman et al., 1997; Patterson et al., 2002]. The bubbles have the biggest expansion in front of a person and the expansion is smaller at the sides and back of a person, when approaching and standing in line [Ashton and Shaw, 1980; Nakauchi and Simmons, 2002]. The interpersonal zones influence human interaction in various ways, especially if boundaries are crossed, e.g., by stepping too close to another person. In their study, Ducourant et al. [2005] researched whether or not pairs of people walking face-to-face were able to keep a set distance between each other whereby one person of the pair had the task to maintain the distance (Follower) and the other had the task to break the distance (Leader). Ducourant et al. [2005] measured the step duration, length, velocity, and the head movement. They found that people watch each other's movements carefully and are able to react to the motions, ranging from small steps to wide steps, and fast movements to slow movements of other persons with a slight delay of 200-300 msec, which increased significantly with increasing distance (from 1 to 3 m) from each other. Furthermore, Ducourant et al. [2005] points out that because of the delay of 200-300 msec in the Follower's motions, the motion of the Leader was not fully anticipated beforehand. Considering that goal-directed motion is interpreted easier, the missing goal-directedness of the Leader's motion and the explicit task to break the distance might have interfered with the prediction of motion beforehand.

Ducourant et al. [2005] also suggests that heuristics such as always keeping a safe distance in form of the intimate zone are the reason for reacting faster on the whole body-motion of the Leader. Therefore, Ducourant et al. [2005] suppose that the difference in the delay of motions of the person who follows, is due to the higher urgency to react faster at smaller distances because at short distances people are able to collide faster.

3.5.2 Neuroscientific Link: Estimation of Social Distances and Coping with Social Life

Neuroscientific findings show that the ability to interpret motion of other humans, as well as sensing and coping with different interpersonal distances are interlinked [Kennedy et al., 2009]. Interpreting the information provided by human body motion is essential in coping with everyday social life, as is the ability to estimate the appropriate distance between oneself and an interaction partner.

Neuroscientists have found that the region of the human brain that shows activity when humans stand close together is the amygdala [Kennedy et al., 2009]. The amygdala is known to trigger emotional reactions, especially in situations in which the boundary of an interpersonal zone is violated. In triggering emotional reaction, the amygdala regulates the interpersonal distance maintained between humans [Kennedy et al., 2009]. This might be evidence for the "distance-sensing process" within humans proposed by Hall [1966, p.115]. Furthermore, Kennedy et al. [2009] suggest that there is a connection between the brain region prefrontal cortex, which also interplays with the amygdala when people make inferences about other people's mental states cf. Section 3.1.3. Kennedy et al. [2009] point to the fact that people with dysregulations in their prefrontal cortex also experience problems with their everyday social lives (cf. Section 3.1.3) and also have problems finding the appropriate interpersonal distance when interacting with others, e.g., these people would stand 1 cm in front of another person without recognising or being able to empathise the opposite's discomfort.

Summing-up: Humans want to maintain interpersonal distances and are good in estimating distances between themselves and others. The unwanted violation of these boundaries increases the level of uncomfortable feeling, especially, if a violation of the intimate zone occurs. The crossing of boundaries must not always be connected with a very bad or repulsive emotion or vice-versa a bad intention. In the context of everyday life, the human distance estimation and the ability to detect goals behind trajectories of human motion is a powerful ability to act and react fast and appropriate in different situations. The crossing of boundaries of personal zones could emphasise the communicative factor of whole-body motions, for example, in a blocking situation. Therefore, changes in interpersonal distance have certainly a communicative and spatial effect on the interaction partners, who need to spatially coordinate. The change in distance is characteristic of whole-body motion which Van de Weghe et al. [2006] suggest to represent to describe moving entities in space in relation with each other.

3.6 Spatial Coordination via Interpersonal Distances in HRI

Research regarding proxemics in HRI is mostly concerned with the question of how to increase the feeling of comfort of the user in interacting with a robot, in other words, identifying what is a comfortable interaction distance for the user and / or participant in a study. The predictability of the robot's motions, the overall degree of comfort with the robot, and the increase or decrease of the interaction distances is interrelated.

The higher the predictability of the robot's motions, the higher the general degree of comfort, which leads to a decrease in the comfortable interaction distance between the human and the robot. When a human is too close to a robot, often the human feels uncomfortable and tries to increase the distance. In contrast, Walters et al. [2006] report on results that suggest that participants at an initial encounter with a robot take up distances from the it that are comparable with Hall's personal - and social zone cf. [Walters et al., 2008].

3.6.1 Factors that Influence the Interpersonal Distance in HRI

A popular scenario in HRI research on finding a comfortable distance between a human and a robot is the *approach scenario* [Argyle, 1988; Walters et al., 2005b,a, 2007, 2011; Takayama and Pantofaru, 2009; Mumm and Mutlu, 2011]. The listed studies are similar in that either a robot was approached by a human or a human was approached by a robot. There were no other tasks or cover stories involved. However, the results of these studies indicate that a range of factors can influence the general degree of comfort of human participants in approach situations with the robot. Moreover, these studies take the increasing or decreasing interpersonal distance as a measurement to infer that the general degree of comfort interacting with the robot has changed. This also means that the general degree of comfort influences minimal interpersonal distance, which participants were comfortable with, which in turn influences spatial coordination situations between persons with the robot.

Walters et al. [2011] found in a long term HRI study that as *experience with robots* in general, and *familiarity* with the specific robot increased, the degree of comfort increased and therefore the minimal approach distance toward the robot was decreased by 4 - 10 cm (starting at 32 - 68 cm). Furthermore, Walters et al. [2011, p.137] suggest that "small dynamic changes [2 - 10 cm] in proximity which occur during HRIs are an important area for investigation", as these are changes which may be perceived by the participants unconsciously but show an effect in HRIs.

In addition, Takayama and Pantofaru [2009] found that people with certain *personality traits*, especially people to be neurotic inclined and more introverted people show larger interaction distances within the personal zone. *Attitudes towards robots* also play a role in determining the distance at which these individuals feel comfortable standing face-to-face with the robot: the distance increased when people do not like robots in general cf. [Takayama and Pantofaru, 2009; Mumm and Mutlu, 2011]. Mumm and Mutlu [2011] reported that the *gender and age of the person* interacting with a robot have an effect on interpersonal distances. The task of the participants within their study was to walk across a room towards the stationary robot (Wakamaru) and read a word from a list at the robot's back. While the participants walked towards the robot, it performed in each trail one of the two conditions: direct gazing at the participants, and averted gazing. The results show that women tolerate direct gazes better than men, as the women did not increase distances significantly when the robot increased the length of gaze to the approaching human [Mumm and Mutlu, 2011].

There are further factors which can decrease the degree of comfort and therefore increase the desired distance from the robot for possible interaction situations. *The voice of a robot* (a human voice is preferred) and the *height of the robot* play a role regarding the minimal comfortable distance to be maintained with the robot cf. [Walters et al., 2008].

In their HRI approach study, Takayama and Pantofaru [2009] found that staring at the participant's face in approach situations, made the participant uncomfortable and the minimal interpersonal distance increased, whereas gazing somewhere else was perceived to be more comfortable cf. [Takayama and Pantofaru, 2009]. This confirms the findings that seated people like to be approached from the side rather than directly from the front [Walters et al., 2007]. Approaching from the side signals in a subtle way that the robot is not going to run the person over. The person is able to predict that the path of the robot does not collide with their own position, which makes the person more comfortable cf. [Koay et al., 2007]. Eye gaze in another direction is mostly used when people are passing by each other [Patterson et al., 2002; Nummenmaa et al., 2009; Kirby, 2010].

Butler and Agah [2001] found that in their approach study that participants perceived the robot's speed to be too high when it drove straight towards themselves with a speed of 0.3 m / sec, and naturally the degree of comfort decreased. The authors also found that the speed of the robot could be increased to 0.3 m / sec and up to 1 m / sec as long as the robot's direction of motion signalled that the robot is not going to crash into the person (as soon as the robot started to arc 20 degrees / sec) cf. also [Yoda and Shiota, 1996]. Furthermore, Butler and Agah [2001] reported that the participant's minimal comfortable distance to the robot passing after approaching either straight or arced ranged between 25 cm for arced approach - 55 cm for the straight approach behaviour. This outcome again shows that manner of moving influenced the minimal comfortable distance between a robot and a human. Butler and Agah [2001] and others suggest that whenever a participant, interacting with the robot, is able to predict the future path of the robot, the participant feels more in control and therefore feels more comfortable cf. [Yoda and Shiota, 1996; Pacchierotti et al., 2006]. Regarding the predictability of a robot's action, Walters et al. [2011] observed that the distance maintained by the human from the robot increased when the robot did not react or broke down. Walters et al. [2011] suppose that this behaviour reflects the degree of comfort. Interesting here would have been a statement whether or not the participants were able to predict the robot's next actions regarding the malfunctioning of the robot.

Walters et al. [2005a] report that 60% of their participants initially kept a distance within the personal zone to the robot when they were asked to approach it, at their minimal comfortable distance, whereas 40% stepped into the intimate zone of the robot. Walters et al. [2005a] suggest that this latter group of people might not have seen the robot as a social entity, due to the fact that there was no reason given by the experimenter why the participants should approach the robot. Walters et al. [2005a] propose that participants should be given a cover story or the participants should be involved in the social robot scenario before distances are measured. The participants could acquaint themselves with the robot, leading them to perceive the robot as a social entity.

In conclusion: for human-robot interaction situations researchers found that human participants carefully watch the physical motions of robots and interpret these motions cf. [Nakata et al., 1998; Breazeal and Fitzpatrick, 2000]. Within this context spatial coordination via increasing and decreasing distance are expected to occur from human participants towards a robot in interaction with each other. Green and Hüttenrauch [2006], for example, suggests that a robot should actively influence a human user via subtle motions, e.g., the robot should turn or move slightly to incite the user to position herself / himself in a better way for the robot to interact with, e.g., to be better detected by the robot cf. also [Green, 2009]. When a person is maintaining Hall's or similar distances to the robot, this indicates that the participant is unconsciously behaving according to human social conventions towards the robot cf. [Walters et al., 2005a] and the media equation in Section 2.2.

3.6.2 Limitations of the Cited Work

A security distance of 30 - 60 cm was maintained by the robot at any time that it approached a human, even if the studies were conducted to find a comfortable distance cf. in particular [Takayama and Pantofaru, 2009]. How people feel about the comfortable interaction distance varies from culture to culture and within a culture, even within an individual person at the moment of interaction and in relation to different situations and tasks cf. [Koay et al., 2007, 2009]. Unless each user is handed a remote control for stopping and directing the robot it is a hard task to accomplish comfortable distances [Walters et al., 2007, 2011].

That is why state of the art research tends to take out as many confounding variables as possible. Overly controlling the interaction leaves a robot and a participant in an experiment without application oriented story or cover story or context whatsoever cf. [Mumm and Mutlu, 2011; Takayama and Pantofaru, 2009; Walters et al., 2005a]. As also discussed by Walters et al. [2011] and Sabanovic et al. [2006], an often mentioned implication is that the interaction is too controlled to model real world interaction situations. Discussable is whether or not the participants feel more uncomfortable when they approach a robot with no idea why it should be approached or why it is approaching the participant. Koay et al. [2007] found, for example, that participants had a significantly lower comfortable approach mean distance (48.8 cm) when involved in a physical interaction compared to no interaction situations (60.2 cm) cf. also [Walters, 2008].

Finding the right interaction distance is a dynamic process as shown in the long term study of Walters et al. [2011] in which comfortable interpersonal distances changed over time. Furthermore, Walters et al. [2011] suggest that small changes in the robot's distance from the participants might be not consciously perceived. Therefore it is also discussable whether or not participants should be told about the aim of study as this might prevent automatic processes to occur. Additionally, questionable is whether or not the uses of visible tape measures on the floor and safety distances of 30 - 60 cm, which a robot had to keep, during a study about interpersonal zones, influence the measurements of interpersonal distances cf. [Walters et al., 2005a; Takayama and Pantofaru, 2009].

Discussion

Identifying the most acceptable distance that a robot should maintain from a human being is, in itself, a difficult challenge, let alone judging the complex variables of speed and braking distances on different ground coatings and of humans stopping suddenly. Taking all personal and situational variables into account might be too complex a task for a robot to compute in time.

The interpersonal distance cannot simply be set to one static distance once and for all, Walters [2008, p.170] demonstrates by presenting, in a table, some HRI scenarios and their relationships with comfortable interpersonal distances of participants from robots. This table presents distances which start at 57 cm and are increased or decreased, depending on the HRI situation, by 2-15 cm. As an interesting illustration, being close to interaction partners does not always bring about negative feelings, even in people who are not intimate with each other; this applies, for example, in team sports or contact sports, and also in collaborative tasks. Even complete strangers are accepted in the vicinity of an interaction partner for a specific amount of time, e.g., in elevators. The challenge is to find out more about the characteristics of communicative whole-body motions that are used in spatial coordination situations in HRI. If the robot is able to figure out the meaning lying behind communicative whole-body motions, it is enabled to adjust the interpersonal distance to the specific situation, e.g., detecting indications (motionings) of an interaction partner wanting to go past or wanting more room.

After a summary of this chapter, the next chapter presents the methodology of the investigations within the scope of this thesis. The limitations of the cited related work, regarding the interpersonal distances, were considered while planning the studies within the scope of this thesis.

3.7 Summary

The sections of this chapter can be summarised in the following three main points.

1. *Humans are well able to interpret motion in any kind of entity. Goal-directed* motions are more legible than randomly conveyed motions because internal goals can be inferred and next actions predicted. The ability to interpret motion is *evolutionary favoured* because it is a fast way to judge "dangerous" intentions of others even if only a few visible cues are available from which to judge. Moreover, *specific brain areas are active* when judging intention from motion. These are also active when inferring someone's mental state (Theory of Mind). There are certain perceptual causality rules, which describe the manner of interpreting but do not explain the reason for these phenomena. Nevertheless, the human interpretation of motion underlies distinct *Gestalt principles*, which imply, for example, that entities presented in close *spatial proximity* are attributed to have be some kind of inter-connection. Furthermore, the Gestalt principle *temporal succession* implies that temporally successive events (actions, motions) are interpreted to be the cause and the effect of each other. Moreover, the Gestalt principle *continuity* stands for the phenomena that humans predict the direction of motion of an entity to continue in the same way. Therefore, any kind of whole-body motion (and motioning) is powerful communicators, especially, when the motion is presented in a goal-directed manner.

2. Motionings *occur before the actual action is performed* so that the interaction partner is able to predict and react. If one wants to design communicative whole-body motions, specific *animation principles* provide important advice: motions that are designed to communicate a specific intention and are also designed to provide information about the next action and need to be conveyed before the actual action takes place (*animation principle: anticipation*). In addition, motion should be conveyed as small subtle motion. Furthermore, repetitions or slight *exaggerations* in the manner of moving increase their legibility and decrease the possibility that motions will interpreted incorrectly. Moreover, the animation principle, *timing*, as well as the Gestalt principle, *temporal succession* emphasise *the importance of timing of successive events* (actions, motions).

3. Humans want to maintain certain interpersonal distances and are good in estimating distances between themselves and others. The unwanted violation of their boundaries induces an uncomfortable feeling, especially when a violation of the intimate zone is about to occur. Other factors that make a person feel uncomfortable also result in humans increasing their minimum comfortable distance from a robot. Therefore, changes in interpersonal distance certainly have a communicative and spatial effect on the interaction partners, who need to spatially coordinate. In human-robot interaction situations, researchers have found that human participants carefully watch the physical motions of robots and interpret these motions cf. [Nakata et al., 1998; Breazeal and Fitzpatrick, 2000]. Within this context, spatial coordination in the form of motionings is expected to occur from human participants towards a robot with which they are interacting.

Figure 3.7 provides a summarised overview of motionings, their characteristics and definitions which have been reviewed within the last two chapters. The figure displays a map for motionings. Most elements of the map were already mentioned in Section 2.6. However, in this chapter, information on how to represent characteristics of whole-body motions is added. Motionings and robotic motion are presented in a qualitative way in the following chapters. Specific and defined characteristics of whole-body motion are changes in distance, changes in the direction of motion, and the position and orientation of the person or robot.

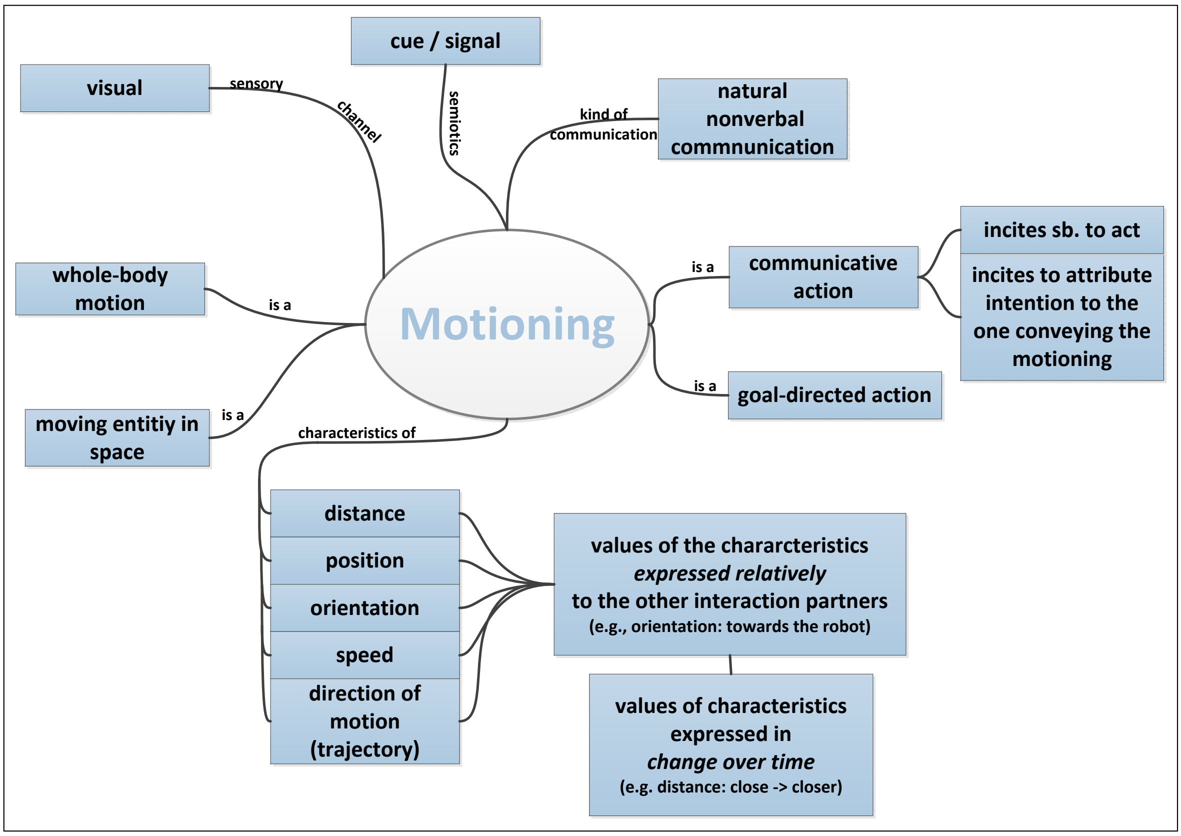

Figure 3.7: *The visualisation displays a map of motionings. A motioning is a goal-directed action. A motioning is naturally conveyed to incite someone to a communicative or spatial action. A motioning is a person - or robot in motion and is considered as a whole and moving entity in space. In a defined space this entity has certain characteristics, e.g., a position, distance, orientation, speed and a direction of a body in motion (trajectory). While the entity is moving, the change of the characteristics is also a way of describing the entity, e.g., change in distance. Furthermore, these characteristics can also be expressed relatively to another entity. Additionally, Van De Weghe et al. [2005] suggests expressing characteristics qualitatively in a small number of categories, e.g., for distance this would be: "closer to", "away from" and "no change in distance". A motioning is perceived via visual channel or an equivalent robotic sensor. In the semiotic sense a motioning is a cue but could also be a signal, depending on the way it is expressed implicit or deliberate.*

Chapter 4

Methodology of the Conducted Studies

This chapter is a detailed description of the methodology of this thesis' investigations which was introduced in Chapter 1. In the following, the methodology (and contribution) of conducted investigations of the next two chapters, Chapter 5 and Chapter 6, are presented. The results of these investigations contribute to the discussion of the potential of communicative whole-body motion in HRI. Each chapter presents a study, which was conducted to provide answers to Q1 and Q2.

These studies are conducted to discuss the potential of communicative motions in HRI from the interpreting and conveying perspective of a human in interaction with a robot and to provide answers to robotic conveying and interpreting role in interaction with a human.

The initial situation is a narrow passage in which two interaction partners (robot, human) want to pass each other but there is not enough room to do so without managing their interpersonal space, in particular, because the robot is blocking the passage accidentally. The spatial coordination in this situation is analysed. Having a different question in focus results in having another side and direction of the interaction in focus. Therefore, the initial situation is embedded in two scenarios, one for each question. Figure 4.1 displays the two study settings separately to present differences but more importantly to stress the similarity of the study settings and situation in focus. It is always the same situation but different roles of an interaction are in focus. The situations for each study are subsequently explained in the next sections.

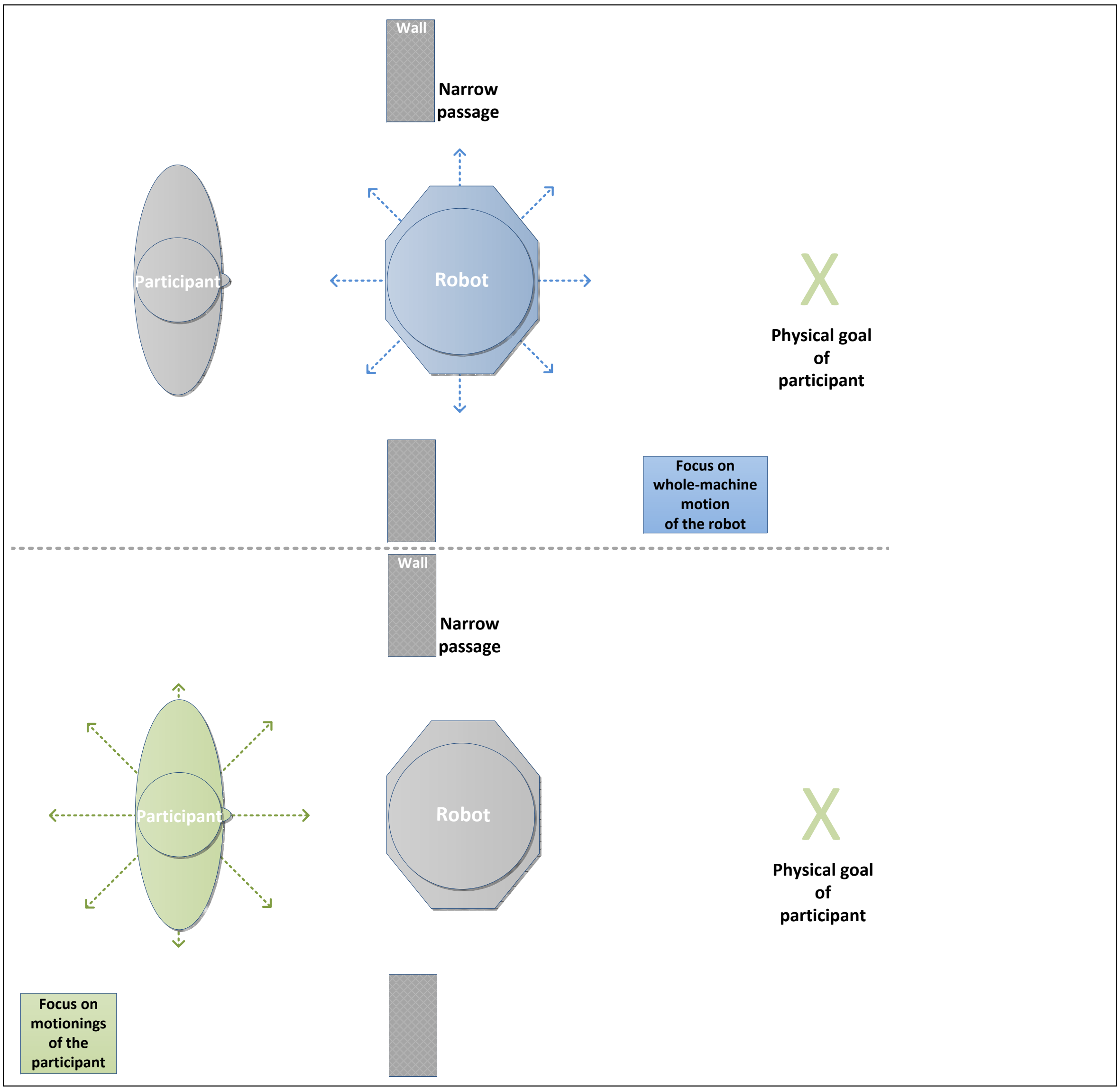

Figure 4.1: *This figure illustrates the encounter between a robot and a human in a narrow spot in an indoor environment twice to present differences and similarities between both investigations conducted within this thesis. The different foci of the investigations are highlighted by the blue colour of the robot and green colour of the participant. The similarities are obvious. In both investigations a robot is blocking the narrow spot and the human has a physical goal to reach which is located behind the robot (represented by the green 'x'). The top illustration presents the study on robotic motion patterns of the robot. The blue colour of the robot and the arrows emphasise the investigative focus which is on robot communicative motion. The question here is: how are these motion patterns are interpreted by the approaching human participant (Q1)? The potential motion patterns of the robot are presented by the dotted arrows around the robot pointing in different directions. The lower illustration presents the similar study setting and the same initial situation. Here, human motionings (potential ones displayed by the green arrows) are in the focus and emphasised by the green colour. The questions here is how to find, define and describe human communicative whole-body motion for a robotic system to interpret (Q2).*

4.1 Investigating Robotic Motion Patterns

Chapter 5 focuses the robot's nonverbal interaction towards the human. More precisely, the chapter presents the investigation of robotic motion patterns regarding the interpretation of these by the participants of the conducted study. Question Q1 is the important question, here.

Q1: *To what extent does a human attribute intention to a robot in motion? Considered from the other perspective: which characteristics of robot motion are important to convey the robot's next action to the human?*

The focus of Q1 is to investigate goal-directed robotic motion pattern. A study is explicitly designed to test how humans interpret goal-directed motion patterns conveyed by a robot. Therefore, eight different robotic motion patterns are created, which are embedded in the same study setting. These robotic motions patterns implement a variety of conditions: crossing the narrow spot or not, driving towards or away, driving to the side or not. The study settings comply with the initial situation in focus of this thesis: the study is conducted in a narrow corridor. An emergency fire door frame narrows the corridor. Participants need to reach a certain room therefore they need to walk along the corridor. They encounter the robot in the narrow passage. The robot initiates one of eight motion patterns or strategies to pass by. These robot patterns are primarily goal-directed but are not explicitly designed to incite the participant to move somewhere. This is done to provide a first step toward investigating communicative robotic whole-body motions. The questionnaire data and observations provide an overview of how, goal-directed motion patterns have an effect on the human attribution of intention to the robot. The investigation is also conducted to get an idea of how to cope with uncontrolled robot motion. In addition, it is also a preparatory work for the next investigation of human motionings towards a robot (Q2).

4.2 Investigating Human Motionings

Chapter 6 focuses on the human nonverbal interaction towards the robot. More precisely, human motionings towards a robot are investigated. Q2 is the underlying question in this chapter.

Q2: *Which characteristics or motion patterns of human whole-body motion are relevant for conveying intention towards a robot? What, in the human whole-body motion, conveys the information to predict the actions or intentions upon which a robot should act? It is also the question of how to find, define and describe human communicative whole-body motion for a robotic system to interpret.*

The investigations for Q2 focus on a special kind of human, goal-directed, and communicative whole-body motions, motionings. Motionings were preliminarily defined in Section 2.6. The description of motionings within the definition is still very general, as these questions are not answered yet: Which are the describing characteristics? And what are the specific values of the characteristics? Therefore, as next step in the investigations, motionings are precisely investigated. Motionings are goal-directed and inform about the underlying intention. Additionally, motionings have the purpose to incite the interaction partner to act even if this interaction partner has not got the ability to interpret this kind of communication as body language in general is an inherent part of human communication [Knapp and Hall, 2009]. The investigation of human motionings is conducted to refine the definition of motionings (cf. Chapter 2.6). Therefore, this investigation is not only a contribution to research about how humans "naturally" and nonverbally interact with robots but also provides insight into how motionings for a robot can be designed. Furthermore the investigation provides information on how human motionings can be represented for a robot. To meet the requirements, a new study is designed. Compared with the study on robotic motion patterns, participants take part in a longer interaction period with the robot but encounter a similar situation: a robot is blocking a way out of a room which the participants want to leave. This scenario is created explicitly to observe human motionings towards a robot, which are expected to be about the problem that the robot is blocking the way. Embedding this situation in a longer interaction context avoids that the conveyed motions are the result of a sudden encounter of robot, cf. Chapter 6. The discussion of the results of the study is divided into several sections. The three main ones are summarised in the following. Subsequently, the human whole-body motions are analysed qualitatively on basis of the video data of the study. A coding scheme is created for describing in detail human whole-body motions on the basis of the qualitative analysis. This is done to have a way of identifying motionings preliminary and refine the definition of motionings afterwards. The next section regards the question of how to describe the motionings on the basis of their characteristics (distance, trajectory, position, orientation). The important goal is to find patterns of values of those characteristics that stand for the earlier identified categories of the coding scheme to validate them on the one hand and to analyse a way of describing and representing motionings for a robotic system on the other hand. As a result a special coding scheme for the characteristics of motionings is created and discussed. Further sections discuss motionings found in different situations and refine the definition of motionings.

Subsequently, to these investigations Chapter 7 presents a precise definition of motionings and ends with three heuristics which provide information of how to cope with the powerful potential of robotic and human whole-body motion for the state-of-the-art or today's social robots in HRIs. Additionally Chapter 8 discusses on-going research which is conducted on the basis of the results of this thesis.

4.3 Observational and Exploratory Case Studies

The aim of the studies is to explore on the one hand whether and by which means human participants attribute the planned intention to the robot conveying whole-body motions (Q1) and on the other hand the aim is to observe and define motionings of a human participant towards a robot which are conveyed in a natural manner (Q2). For both approaches priming participants about body language or informing them about the research questions or explicitly asking how they would like to react, would not be applicable, as natural behaviours are expected.

Therefore, the studies conducted for providing information for Q1 and Q2 are conducted as exploratory and observational case studies. Babbie [2010] reports that "[...] exploratory social research can dispel some misconceptions and help focus future research." Moreover, Ryan and Bernard [2003, p.86] argues for exploratory phases of investigations in a similar manner: "If researchers fail to identify important categories during the exploratory phase of their research, what is to be said of later descriptive and confirmatory phases? " Sabanovic et al. [2006] and Walters et al. [2011] argue for observational studies as they provide information about natural behaviour, which would not be obtained in a laboratory or in very controlled experiments. Furthermore, Walters et al. [2011] suggest to balance controlled study settings and engaging cover stories in the HRI studies so that the studies are structured but also not boring for participants. Runeson and Höst [2008] define guidelines for conducting and reporting case study research which are not only helpful in software engineering but also applied in this case too as the previously mentioned exploratory and observational study and the case study of Runeson and Höst [2008] are comparable. Runeson and Höst [2008] report that *the primary objective of a case study is to explore a phenomenon in an exploratory or observational way.* The design of the study is flexible. This means that a study in such a way may collect not only qualitative data but also quantitative data cf. also [Ryan and Bernard, 2003]. A case study has to define research questions to be answered in the course of the study and / or to provide in information to later formulate hypotheses or generate ideas. Case studies are a popular methodology to research interaction between people in sociology and psychology with questions about social phenomena. Case studies are suitable for researching dynamic characteristics of real world phenomena. Naturally, there is always a trade-off between the level of control and realism [Runeson and Höst, 2008]. That is why; there are always limitations on both sides. Moreover, Argyle [1972] states that one cannot claim to examine interaction if the designed experiment is conducted in a lab and eliminates all confounding variables. This is not interaction and much less social interaction. The focus of this study is interaction-centred, see Chapter 2.1. That is why, the conducted studies are not controlled by any defined positions and postures the participants have to take, e.g., putting crosses on the floor might also prevent people from displaying natural behaviour, in particular, subtle body motions. Furthermore, Argyle [1972] recommends distracting participants from the underlying research topic or questions by embedding the study into a plausible context and / or cover story, e.g. a different task that they have to perform, and a cover story that provides a reason why they should fulfil a task. Furthermore, he recommends analysing videos of interaction sequences of observational studies and integrating the results from various sources like questionnaire, interviews and the study itself. This also means qualitative and quantitative data are analysed. Figure 4.1 displays the core of the studies. The core situation is that a robot is blocking the way for a human who wants to proceed to her / his goal. Regarding the requirements and recommendations for observational case studies, the core situation needs to be embedded into a credible context. Chapter 5 describes the study setting for robot motion patterns (Q1) and Chapter 6 describes the study settings for observing human motionings (Q2).

Chapter 5

Investigating Robotic Motion Patterns

This chapter presents the investigation of robotic motion patterns (RMP). The reason for analysing entire motion patterns not single motionings of the robot as defined in Chapter 2.6 is that first of all an overview was needed. This overview is realised by an analysis of the current state of robot motion patterns. The advantage of displaying simple motion patterns (in the style of Heider and Simmel [1944]) is that these motion patterns are similar to a lot of scenarios of HRI presented by researchers throughout the HRI community cf. 'approaching' scenarios [Walters et al., 2007] and 'passing by' scenarios [Pacchierotti et al., 2006], and 'home and office tour' scenarios with corridors or different narrow spaces cf. [Hüttenrauch et al., 2009] and Chapter 2 - 3. Therefore, this chapter provides an overview of the human interpretation of such robotic motion patterns in a passing scenario in a corridor with a narrow place. Furthermore, to investigate single motionings by a robot, motionings need to be precisely defined and investigated to generate an idea how to design such motionings for robots. Therefore, the following investigation has been conducted to provide a starting point for investigating the potential of communicative whole-body motions in HRI - starting with the robot role of an interaction. As this investigation is an overview, it is also a preparatory work for the next investigation of human motionings towards a robot (Q2), which is presented in the next chapter (Chapter 6). Regarding the definition of motionings, first of all an idea needs to be generated as to when exactly human motionings are occurring, so that they can be observed, and more precisely defined, before they can be used in HRI. This chapter starts with a current-state analysis of robot motion and its human interpretation.

Therefore, this chapter's guiding question is:

Question about robot motion:
Q1: *To what extent does a human attribute intention to a robot in motion? Or asked from the other perspective; which characteristics of robot motion are important to convey the robot's next action?*

Figure 5.1 displays an overview of the thesis' structure and the placement of this chapter within the overall structure.

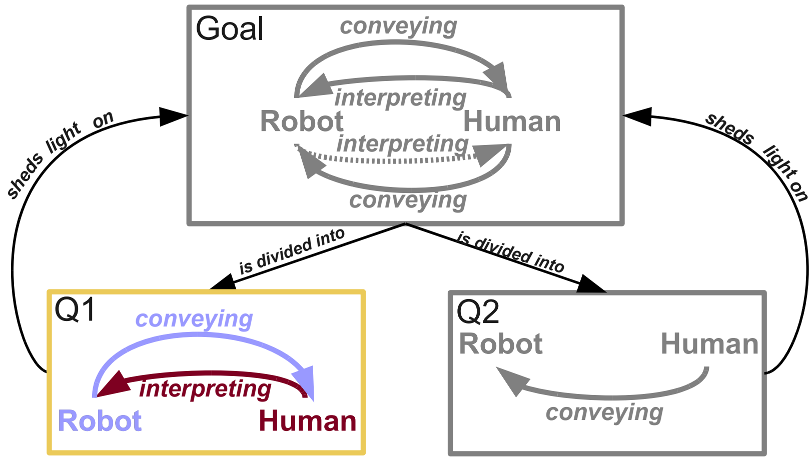

Figure 5.1: *This chapter is about the investigation of robotic motion patterns. The investigation is displayed by Q1, in the lower corner on the left-hand side in this figure. The investigation of the human interpretation of current robot motion has priority in this chapter. (Therefore, Q1 is not divided into Q1.1. and Q1.2. in this figure.)*

This chapter presents not only the main analysis of robot motion patterns but also a short analysis picking out human single motion intervals, which are similar to the preliminary definition of motionings (Section 2.6), and an analysis of the reason for their occurrences. This is done to provide a full understanding of the effect of robot motions on humans and to prepare for the next investigation on human motionings. Therefore, the guiding question is divided into the main question Q1.1 and a minor question Q1.2.:

Q1.1.: What are the characteristics which change the human interpretation of robot motion? Why is the human attributing an intention to a robot?

Q1.2.: When is the human motioning a robot? What are the reasons for spatial coordination? This question is the guiding question for a survey on single human whole-body motions and their reasons.

These questions mark off the range of nonverbal communication via robotic whole-body motion from single motion intervals to motion patterns.

To shed light on these questions a study is planned which needs to fulfil the following requirements. These requirements are derived from the goal of this thesis:

The study scenario needs to comply with the initial situation, a passing by situation in a narrow space in which the robot and the human need to spatially coordinate in order to pass each other. Furthermore, the robot needs to convey motion that a human participant is able to observe so that it can be interpreted. The participants of the study are not allowed to know that they need to interpret the motions of the robot prior to the study in order to receive natural interpretations of the robot motion, as the focus lies on natural and nonverbal communication which occurs without priming or practise. The background information for this requirement is that humans interpret motion no matter if the conveyed motion was intended [Breazeal and Fitzpatrick, 2000].

Outline of this Chapter In the course of this chapter, the exploratory case study is described, which is conducted to explore robotic motion patterns, their interpretation by humans and to derive ideas how to conduct the study on human motionings. An exploratory case study fulfils the requirements cf. Section 4.3. The resulting video and questionnaire data is analysed and discussed in separate sections. Consecutively, three sections of data analysis and discussion follow:

- Section 5.2 presents general results including demographic results.
- The main Section 5.3 comprises the analysis of the questionnaire with open and closed questions about the interpretation of the encountered robot motion patterns. This section presents information to Q1.1.
- Section 5.4 presents the analysis of single motion intervals of the human and robot. The human motion intervals are chosen because they are corresponding to the definition of motionings given in Chapter 2.6.

The last section comprises general observations, which were made during the study and discusses the importance for robotic systems to be aware of their own motion. Every motion might confuse the human interaction partner because she / he associated a wrong intention to the conveyed motion.

5.1 Exploratory Case Study of Robotic Motion Patterns

To fulfil the requirements for this study and to comply with the initial situation a scenario was invented that included an encounter of the robot BIRON and a participant in a corridor at a narrow spot (fire door frame) within the corridor. The exploratory case study took part at an office building at Bielefeld University, Germany. This scenario and results are partly presented in Peters et al. [2011]. The participants were recruited for a HRI study but did not know that they would meet the robot while walking along that corridor as they expected the study to start two floors above that corridor. This setting guarantees that the participants wanted to pass by the robot and that any kind of interpretation of the participant is spontaneous. The robot conveyed eight slightly different motion patterns when the participants walked along the corridor, thus they saw the robot either driving towards, away, standing, and turning at the narrow spot in the corridor.

5.1.1 The Narrow Corridor Setting

This corridor is 1.85 m wide and about 12.63 m long. It has a special narrow spot, an emergency fire door frame. This fire door frame creates a spatial bottleneck of 1.15 m. This feature is used in the study setting to create a narrow passage in which the robot and a human have to coordinate in order to pass by each other cf. Figure 5.2. The figure displays BIRON standing in the narrow spot in the corridor thus leaving about 32.5 cm at each side of the narrow passage when BIRON is standing in the middle of the door frame. The participants turned into the corridor, having approximately 8.4 m between them, the narrow passage, and BIRON. BIRON initiated eight different motion patterns. In the very beginning of those motion patterns, participants saw BIRON either driving towards the narrow spot and facing them or standing and facing them.

Figure 5.2: *This figure displays the robot BIRON in the corridor at the narrow passage (fire door frame). This corridor is 1.85 m wide and about 12.63 m long. The fire door frame creates a spatial bottleneck of 1.15 m. This leaves approximately 32.5 cm on each side of BIRON standing in the middle of the door frame. During the trials, participants turned into the corridor from the right bottom edge of the picture. This picture also presents the initial view of the participant when he / she turned into the corridor. The picture also presents the view of the external camera during the trials. In addition, it depicts the robot BIRON in its initial position within the static setting cf. further descriptions, in particular, Section 5.1.5.*

Typically, the corridor is used by employees and students of the university to reach lecture halls, offices and the stairway. Signs on the floor and walls of the corridor informed them that a robot was working and moving in this area, as well as that the area was temporary under video surveillance. An external camera recorded the scene from an upper elevated position filming the back of the participants as they passed by the robot cf. Figure 5.2.

5.1.2 Cover Story for the Participants

Participants were recruited to take part in a HRI study. Participants were told that the study would take place two stories above the corridor. In order to reach the study room, they had to take the corridor where the robot was placed. Therefore participants took part in the study, unaware of the details. The participants were informed shortly after they took part in the human-robot passing situation in the corridor that the actual study was already over. They were asked if they would fill in a questionnaire about the encounter and were asked if the video data could be used.

5.1.3 Experimenters

For comparison reasons, the experimenter triggered the robot's program via remote control so that one of the eight motion patterns was initiated randomly as soon as the participants turned into the corridor. This was done to be independent from the erroneous human detection rate of the robot at length of 8-10 m. The best human detection rate lies at about 3 m because more laser beams of the laser scanner are reflected at human legs when they are closer thus returning more data to compute and detect human legs. During each study trial two experimenters were hiding from the participants but were able to observe the scene and stop the robot in case of an emergency via remote control.

5.1.4 The Robot BIRON

BIRON, is a combination of a two-wheeled *PatrolBot*^{TM} and *GuiaBot*^{TM} by Adept MobileRobots,[1] cf. Section 2.2 for the general classification of this robot. Figure 5.3

[1]Adept MobileRobots www.mobilerobots.com, *GuiaBot*^{TM} is not produced any more.

displays the BIRON and its equipment. BIRON -the (**BI**lefeld **R**obot compani**ON**) is an advancement of the BIRON robot in Spexard et al. [2007]. A detailed description of the new BIRON is found in Peters et al. [2011]. In the following, only the parts of the robot which are used in the study are described. The robot has a laser range finder (SICK LMS200) which covers 180° in front of the robot at 30 cm above the floor. The data of the laser range finder was used to build a map of the environment and build hypotheses of human legs in the robots vicinity. The camera is mounted on the top of the robot and recorded video view of BIRON for later analysis. Besides two wheels BIRON has two rear casters for balance and is constructed with a differential drive (2 degrees of freedom: translation and rotation). This enables it to turn on the spot and drive curves while driving forward but BIRON is not able to drive directly to its left or right (no holonomic drive). side. Thus, in the following description of BIRON's motion patterns, sideward motions stand for curved motions but never motions in a right-angle without turning. BIRON has an overall size of approximately 0.5 m (w)×0.6 m (d)×1.3 m (h). BIRON piggy-backs two laptops with Intel Core2Duo©, 2GB main memory, and Linux to provide the computational power.

Software

The robot BIRON has a software system which has been constantly developed over the last eight years. To implement the motion patterns of BIRON, BonSAI (BirON Sensor Actuator Interface)-API is used. BonSAI[2] is a robot behaviour abstraction layer which is written in Java. It provides an interface to various functions of the system of the robot, for example SLAM and basic navigation with obstacle avoidance. For more details concerning the entire system and BonSAI cf. [Wachsmuth et al., 2010]. I implemented eight motion patterns for BIRON with help of BonSAI. The motion patterns were randomly[3] initiated when the experimenter sent the command. Apart from the initiation of each trial the robot operated autonomously and was driving the preprogramed paths of the specific motion pattern. Each pattern contained a path which the robot had to drive along to reach the overall goals. Although the robot was able to detect people, the experimenter triggered the initiation. This was done as the purpose of the study was not to test the system but to observe the human and robot in a passing by situation and to receive comparable starting points within each

[2]see `https://code.ai.techfak.uni-bielefeld.de/bonsai/` for the BonSAI API

[3]The motion patterns were randomised within each setting which included the same starting point cf. Section 5.1.5

Figure 5.3: *This figure depicts the robot BIRON - the (**BI**lefeld **R**obot compani**ON**). The robot is a combination of a two-wheeled PatrolBot^{TM} and GuiaBot^{TM} by Adept MobileRobots. The on-board camera is used to record BIRON's view for later video annotation. There is a laser range finder (SICK LMS200) inside the base front with a scanning range of* 180° *and scanning height at 30 cm above the floor. The arm with gripper was not used and folded up during the study.*

pattern. The human detection rate is erroneous at a length of 8-10 m from the person as the laser scanner has laser beams at about every two degrees thus resulting in only a few or no data points at a length 8-10 m to compute human legs. Furthermore, the basic obstacle avoidance was running but set to a minimum to ensure the person was not run over during the trials but the program would not interfere with the motion patterns.

5.1.5 Robot Motion Patterns in the Narrow Corridor

Participants encountered BIRON, which initiated one of the eight different motion patterns (MPs or passing strategies). Figure 5.4 displays the settings of the study cf. also Figure 5.2 to get an idea of the corridor. Figure 5.4 and also Table 5.1 provide an overview of the eight different passing strategies and further classification into more and less blocking, and also defensive and offensive strategies. The purpose of the MPs was to find out how motion patterns and which motion patterns would be interpreted as communicative acts of the robot towards the person and if the participants could attribute an intention to the robot. In this study, the passing strategies contain entire motion patters with longer continuous parts of motion, changes in the direction of motion and changes interpersonal distance between robot and human. The question here is whether these motion patterns are perceived as part of communication and a distinct intention. If so the humans will interpret the motion and attribute an intention to the robot. Within the eight MPs, different parameters of the patterns are changed to examine how these take an effect on the interpretation of motions.

The patterns can be classified in three different ways, dynamic and static setting, less blocking and more blocking strategies, and strategies in which BIRON is not crossing the door frame towards the participant (defensive) and strategies in which BIRON is crossing the door frame towards the participant (offensive) cf. Figure 5.4.

The eight MPs are divided equally into two settings: *the static setting* includes four MPs and the *dynamic setting* includes four MPs either. The dynamic and the static setting differ in the position and motion of BIRON, participants would witness when they came along that corridor. In the *static setting* participants, who entered the corridor saw the robot standing 8.4 m away in the narrow spot in the hallway (door frame of an emergency fire door). On sight of the participant, the robot was triggered to initiate one of four motion patterns randomly within the static setting. In the

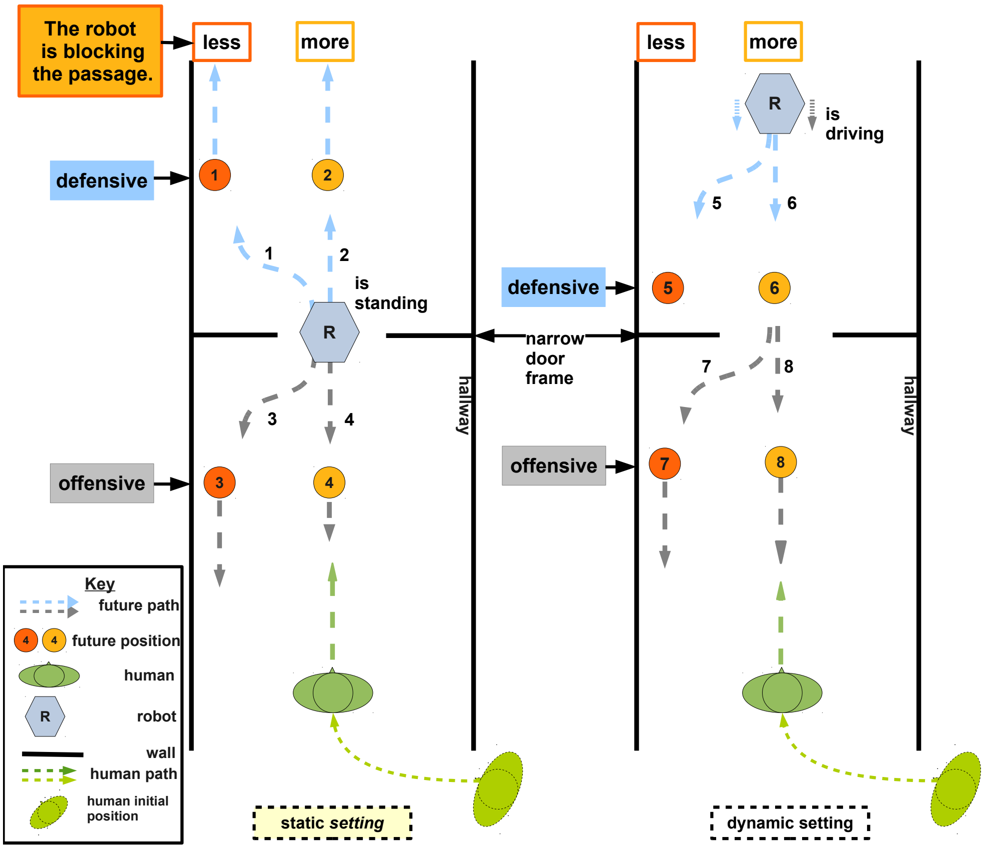

Figure 5.4: *This figure displays the 2 x 4 motion patterns (MPs), the robot BIRON initiated randomly. There are two settings with each four different strategies how BIRON is behaving after the experimenter triggered the initiation of a MP. The settings differ in the starting position of the robot. That is why the hallway with narrow passage on a fire door frame is depicted for each setting. The left hallway depicts the* `static setting`*. Here, the robot is standing still in the door frame thus completely blocking the passage for an approaching person. The person is depicted with the green elliptic shape. In the static setting, the person sees the robot standing still at first and then it initiates one of the four static MPs. The future positions of these four MPs are depicted with red and orange numbered circles (1-4). Dashed arrows point the path, which BIRON takes for each MP. The right hallway depicts the* `dynamic setting`*. Here, the person sees BIRON driving towards the narrow passage. BIRON initiates one of the four passing strategies (MP), depicted by the red / orange circles with numbers from 5-8. The eight MPs or passing strategies are also divided into* `defensive and offensive strategies` *(blue, grey, boxes and arrows). Within the defensive strategies, the robot does not cross the doorsill (circles 1, 2, 5, 6). The offensive strategies are MPs in which the robot crosses the doorsill (circles 3, 4, 7, 8). The 8 MPs are also subdivided into 4 strategies in which BIRON is* `more or less blocking` *the way for a person (red and orange boxes). The four MPs in which the robot drives to the side are also trajectories away from or past the human path (circles 1, 3, 5, 7). The four MPs, in which the robot blocks the path for the person, are the patterns which do not provide any indication of how this situation may be solved (circles 2, 4, 6, 8). Table 5.1 displays this relationship of MPs with corresponding colours.*

dynamic setting participants turned into the corridor and saw the robot driving towards the narrow spot at about 11 m from the participants. Then the robot initiated one of the four dynamic patterns. Thus BIRON was started before the participants turned into the corridor and was triggered to initiate randomly one of the four MPs. The difference here is also that participants of the dynamic setting do not get to see a pause in the motion of BIRON at the beginning of the motion patterns. The missing pause and therefore missing beginning of a new action phase is expected to make it more difficult for the participant to figure out meaningful motion segments cf. Section 2.6 and Section 3.3.1 for information on action segmentation. Furthermore, the abrupt begin of motion, as provided in the static setting is expected to evoke more attention or urgency to react to the MPs and therefore different interpretations of the participants. The static patterns are numbered from 1-4. The dynamic patterns are numbered from 5-8 cf. also Table 5.1 and Figure 5.4.

Each setting is also divided into two *defensive strategies* and two *offensive strategies*. These terms defensive and offensive are derived from the way people can drive their cars: defensive driving vs. offensive driving. Each defensive and offensive strategy has a motion pattern in which the robot drives to left side (participant's view) or stays in the middle path of the corridor. Only the left side is considered because of the Germany traffic rules, which are in Germany also a social convention to follow while walking, similar to people in the US, [Pacchierotti et al., 2006]. *Defensive strategy* means that BIRON did not cross the threshold of the door frame within a defensive motion pattern whereas *defensive motion patterns* included crossing the threshold of the door frame towards the participant's initial position.

At the very beginning of all MPs, the robot was either driving on a collision path towards the participants or was standing in the middle of the door frame. After that the MPs continued on a blocking and collision path or continued with another strategy. Therefore each setting can be also described when dividing the MPs into two less blocking and two more blocking strategies of BIRON. The *Less blocking* strategy means that the robot drove to left side (participant's view) at one stage of the respective motion patterns thus the robot signalled another path than collision path. The *more blocking* strategy summarises the MPs in which BIRON stay in the middle of the hallway thus having a collision path with the approaching participant. The MPs within this strategy are expected to elicit fewer interpretations of participants attributing an avoiding intention to the robot whereas less blocking MPs are expected to be associated more with an avoiding intention of BIRON.

The purpose of dividing the MPs into these groups static, dynamic, more and less blocking, and defensive or offensive is to examine whether the interpretation of the participants differs in any way, e.g. the participants could take the indication of the direction of the motion to the side (less blocking) as a cue to attribute the intention passing by or avoiding to the robot.

The terms, static / dynamic, less blocking / more blocking, and defensive / offensive (driving) created to describe and divide results into classes of motion patterns. The next paragraphs explain each pattern. Within this chapter all directional descriptive terms are stated from perspective of the participant.

Static Setting

The initial position for BIRON within the static setting is in the narrow door frame in the corridor. The participant saw BIRON standing still in the middle of the door frame while turning into the corridor. Then experimenter initiated one of the static motion patterns when the participant turned into the corridor. Figure 5.2 depicts BIRON in its initial position in the door frame in the corridor the study was conducted.

Motion Pattern 1 (MP 1) defensive, less blocking: The robot turns around and drives into the same direction as the person is walking. In the qualitative way of the classification of trajectory, the trajectory of BIRON's motion is "away" cf. Section 3.4.3. After BIRON has turned, it drives to the left side of the corridor and keeps driving along that side. This is a defensive strategy because BIRON does not cross the doorsill of the emergency door. Driving to the side is also a signal that BIRON makes more room for the approaching person. That means BIRON blocks the way of the person less, cf. number 1 in Figure 5.4 (p.88) and Table 5.1 (p.92).

Motion Pattern 2 (MP 2) defensive, more blocking: The robot turns around and drives into the same direction the person is walking to but compared to MP 1 it stays in the middle. The trajectory of BIRON's motion is away. The strategy of this pattern is defensive in only the way that it does not drive over the threshold. BIRON blocks the way more for the person compared to motion MP 1, cf. number 2 in Figure 5.4 and Table 5.1.

Motion Pattern 3 (MP 3) offensive, less blocking: The robot drives towards the person and to the left side. The strategy of this pattern is offensive as it crosses the threshold and drives in the direction of the person. It also makes room and therefore blocks the way of the person less. The robots signals that it is not running the person over, cf. number 3 in Figure 5.4 (p.88) and Table 5.1 (p.92). The trajectory of the motion of BIRON is towards and then past.

Motion Pattern 4 (MP 4) offensive, more blocking: The robot drives towards the approaching person and stays in the middle of the corridor. The strategy of this pattern is offensive both ways; the robot drives over the threshold towards the person and stays in the middle without avoiding the person, cf. number 4 in Figure 5.4 (p.88) and Table 5.1 (p.92).

Dynamic Setting

Motion Pattern 5 (MP 5) defensive, less blocking: The robot drives towards the threshold but turns before it reaches the threshold to the left side and stays there. This pattern is of defensive strategy. The robot in this pattern signals via its motion that it is avoiding the person and letting her / him pass by, cf. number 5 in Figure 5.4 (p.88) and Table 5.1 (p.92). The trajectory of the motion of BIRON is towards and then past.

Motion Pattern 6 (MP 6) defensive, more blocking: The robot drives towards the threshold and stops in the door frame. The strategy of this pattern is defensive as the robot stops and does not cross the threshold. The robot does not make room for the approaching person - BIRON blocks the way more compared to MP 5, cf. number 6 in Figure 5.4 (p.88) and Table 5.1 (p.92). The trajectory of the motion of BIRON is towards.

Motion Pattern 7 (MP 7) offensive, less blocking: The robot drives towards the threshold, crosses it and turns to the left. This pattern has a more offensive strategy compared to MP 5 and MP 6. As the robot turns to the left, it avoids the person, therefore the robot in this pattern blocks the way less, cf. number 7 in Figure 5.4 (p.88) and Table 5.1 (p.92). The trajectory of the motion of BIRON is towards and then past.

Motion Pattern 8 (MP 8) offensive, more blocking: The robot drives towards the threshold, crosses it and drives further towards the person in the middle of the corridor. The strategy of this pattern offensive and leaves no extra room for the person, cf. number 8 in Figure 5.4 and Table 5.1 (p.92).

static setting	less blocking	more blocking
defensive	1 = sideways, away	2 = straight, away
offensive	3 = sideways, past	4 = straight, towards

dynamic setting	less blocking	more blocking
defensive	5 = sideways, past	6 = straight, towards
offensive	7 = sideways, past	8 = straight, towards

Table 5.1: *These tables display the possible passing strategies. BIRON exhibits one for each trial. The numbers and colours correspond to the circles in Figure 5.4 (p.88). The entries towards, away, straight and sideways describe the motion of the robot.* `Less blocking` *means that the robot is blocking less the path for the participants. It moves to the left in order to avoid an approaching person. The trajectories of the motions point either away from, or past the person and are always motions to the side.* `More blocking` *stands for straight motions with no clue how the passing situation might be resolved. The robot is more blocking the way of the approaching person. The motions can be towards and away from the person but always in the way of the approaching person. More blocking and less blocking differ in the trajectory of the motion.* `Less blocking` *strategies are also strategies, in which BIRON signals a trajectory away from or past the approaching person's position.* `More blocking strategies` *are defined as motions which do not signal any other direction of motion as the trajectory of the approaching person.* `Offensive` *motions are forward motions, past the narrow space cf. the door frame in Figure 5.4.* `Defensive` *motions are motions away, towards and past the robot but always motions without passing the doorsill.*

5.1.6 Preparing for Q1.2.

To evaluate the video data of this study with respect to Q1.2., some requirements need to be fulfilled. Q1.2.: When or why is the human motioning a robot? What are the reasons for spatially coordination? These questions are the guiding question for a survey on single human whole-body motions and their reasons.

The corridor is divided into three segments for the video annotation and measurement of positions of the robot and the human in the corridor. segments. Furthermore, to measure the distance between the person and the robot reference points need to be visible in the video when video annotating. The data of the laser scanner is also recorded, so that the distance between a person and the robot can be computed but as mentioned before, the tracking of human legs at a distance of 8-10 metres is erroneous. Furthermore, this way of measuring the distance is not possible once the robot turns more than 90° away from the person.

That is why the map of the entire floor presenting the dimension of all rooms along the corridor was used for later video annotation. More importantly, however, are the "natural" existing reference points in the corridor, such as the tiles on the floor, door frames of the offices, and the tiles on the ceiling. Consequently, an annotation of the dimensions of the corridor was created to be put on video as another layer for later video annotation.

The corridor was segmented into three parts a middle part, a left part, and a right part cf. Figure 5.5. The 50 cm in the middle were segmented as middle part. This was done to match BIRON's width (50 cm) in the middle of the corridor cf. Figure 5.5. A small study and an analysis of where people walked in the corridor when they walked straight along the corridor supported this segmentation as 100% of the participants (N=10) walked in the middle 50 cm of the corridor. The width of the corridor (185 cm) is not equally divided into three parts because the door frame narrows the corridor to 115 cm in which BIRON's widths does not fit in three times. Consequently, the left and the right part are bigger (67.5 cm) than the middle part including the parts of the door frame. Figure 5.2 displays BIRON standing in the middle of the door frame, thus displaying exactly the segmentation.

Video Annotation

Each participant was filmed as soon as they turned into the corridor. The videos are annotated concerning distance between the robot and the participant, the velocity, the global position in the room, and the execution of the motion was annotated for both, robot and human. Apart from the distance, everything else was annotated with qualitative values cf. Table 5.2. The distance was estimated from the video which was equipped with an additional layer displaying the dimensions of the corridor cf. Section 5.1.6.

annotation variable	values
distance	continuous data in metre
velocity	normally, hesitantly, quickly, no motion
global position	left, middle, right, left-middle, left-right, middle-left, middle-right, right-left, right-middle
execution	single steps, continuously moving, no motion

Table 5.2: *This table presents the annotation values which are used to annotate the participants' and BIRON's motion for a preliminary analysis of human motionings and the robot's behaviour at the same time.*

The velocity intervals started and ended whenever there was a change in the velocity. This was estimated by the raters checking the change of the velocity. Afterwards, the velocity was controlled by computing the velocity on the basis of the distance and duration of each annotated interval. A normal walking velocity for humans was set to 1 m/s, ranging between 0.8 -1.2 m/s corresponding to the normal walking speed set by Kirby [2010, p.48]. Everything below was annotated as a hesitant walking velocity and everything above was annotated with a quick walking velocity. The velocity of BIRON was only annotated with no motion and normal velocity as the robots speed was set to 0.8 m / s corresponding with the upper driving speed of robots in a passing scenario cf. Yoda and Shiota [1996]. Beginnings and ends of the global position intervals were annotated whenever there was a change in the global position of the robot or participant. The corridor was divided into three stripes. Figure 5.5 presents these three stripes, left, middle, right and arrows for the other values. The other values are chosen whenever the participants or the robot is moving from one stripe to the other, e.g., left-middle means that the person / robot is moving from the left to the middle, right-left means that the person is walking continuously, thus changing sides from right to left. The annotation, execution, has three values, single steps, continuously walking, and no motion. For this analysis there are only three values important because the goal is to find human single steps as opposed to many steps within a continuous walk. Single steps are small motions and can be considered as abrupt motions when they are flanked with pauses in motion or other changes in the characteristics of motion, e.g., velocity from quick to hesitantly. Single steps are a first sign of motionings cf. Section 2.6. Robotic execution is annotated with jerky motion instead of single steps.

Figure 5.5: *This figure presents BIRON in the corridor and a sketched layer displaying the segmentation of the corridor for the annotation of the global position and its values: left, middle, right, left-middle, left-right, middle-left, middle-right, right-left, right-middle. The arrows stand for a change of stripes and present the walking direction from the participants' perspective, e.g. middle-left means that the person walked or stepped from the middle part to the left part.*

5.2 Demographic Results

The participants were recruited on Bielefeld campus, Germany, for a human-robot interaction study. As mentioned before the participants did not know when their trial started. Participants were greeted in the entry hall of one of the University buildings which is used by the research staff of the Faculty on Technology, so that robots driving around is not uncommon event in that building. The participants were sent to the study room. On that way they had to pass the robot in the corridor in order to reach the room. The participants of the study encountered one of eight motion patterns, which BIRON conveyed.

59 people took part in the study, 56 participants (34% female, 66% male, age: $M = 30.4$, $SD = 7.6$) filled in the questionnaire[4]. The three others said that they had not consciously seen the robot while they were walking along the corridor. The videos showed that they just walked past the robot. All three participants encountered BIRON in a dynamic MP 8 in which it drove to the side. These three participants are not further considered. Most participants have a computer science background (70.4%), 17.9% have another scientific background and 10.7% have no scientific background. However, 82.2% of the participants had seen BIRON before but only 18% had already interacted with it. The next section provides the results of the questionnaire and the analysis of the motion patterns according to the answers of the participants in the questionnaire.

5.3 Analyses of the Questionnaire

Generally, all eight motion patterns (MPs) are compared to each other on the basis of closed question and open-ended questions (free answers). The closed questions are using a 5-Likert-scale (response scale) for answers with 1 being (strongly disagree) to 5 (strongly agree). Table 5.3 and Table 5.4 provide a summary of the description of MPs, which is helpful throughout the analysis of the questionnaire cf. also Figure 5.4 (p.88). While analysing the questionnaire data, the goal is to check whether there are differences in the response behaviour of participants, who have experienced different MPs. The differences are discussed and interpreted.

[4]The explanation of all mathematical notations can be found in the Appendix A in three tables (p. 211 f).

The approach is to compare groups of MPs with each other per question, e.g., static vs. dynamic, less blocking vs. more blocking, defensive driving vs. offensive driving. If none of these groups result in significant differences, all eight MPs are compared to each other to make sure that there are no differences in the response behaviour within other groupings of MPs. This analysis is done because difference in the response behaviour of different MPs indicate which of the characteristics of the MP helps communicating the goal or to look at it from the other side: helps interpreting the goal.

Short Description of MP	Long Description
static vs. dynamic setting	`Static setting` means that participants saw BIRON standing still in the middle of the door frame at very beginning of the MPs whereas dynamic setting means that participants who experienced a `dynamic setting` saw BIRON moving at the very beginning of the MPs.
less vs. more blocking	`Less blocking` means that BIRON took a path other than the collision course with the participants during the MPs whereas `more blocking` means that BIRON is driving on the collision course with the participants (only in MP 2 BIRON is driving on the collision course with the participant but in the same direction the participant is walking.
defensive vs. offensive driving	A `defensive strategy` means that BIRON is conveying defensive driving because it is not crossing the door frame during the MPs whereas an `offensive strategy` is a strategy in which BIRON is conveying offensive driving because BIRON is crossing the door frame and is coming purposely closer to the participants.

Table 5.3: *This table presents three groups (classifications) of the Motion Patterns (MP) with which the MP's are described and grouped throughout the analysis. Figure 5.4 displays the MPs in the hallway.*

5.3.1 Question 1: Perceiving Change of Behaviour

The question, presented in this section, is a closed question asking whether the participants think that BIRON changed its behaviour at all. This question is asked to check

Motion Pattern	Short Description		
MP 1	**static**	`defensive`	*less blocking*
MP 2	**static**	`defensive`	more blocking
MP 3	**static**	offensive	*less blocking*
MP 4	**static**	offensive	more blocking
MP 5	dynamic	`defensive`	*less blocking*
MP 6	dynamic	`defensive`	more blocking
MP 7	dynamic	offensive	*less blocking*
MP 8	dynamic	offensive	more blocking

Table 5.4: *This table presents the description of each Motion Pattern using the groups presented in Table 5.3.*

whether or not participants recognised any change of behaviour of BIRON which is essential for participants to interpret the MPs of BIRON. Furthermore, this question is asked to investigate whether there are any differences in the response behaviour of the participants who have experienced a different MP.

There was no significant difference found when comparing the medians of the MPs within their earlier described groups (classifications): less vs. more blocking, dynamic vs. static, and defensive vs. offensive. This means that the MPs within these groupings were rated for question 1 differently. Consequently, this means that within one group the MPs are still too different.

Further analyses revealed that there are three groups with significantly different medians (Kruskal-Wallis test: $\chi^2(2, N = 56) = 12.98,\ \ p = .002$)[5]. Participants, who experienced **MP 1, MP 2, MP 3 or MP 6 (group 1)** strongly agreed that they had seen BIRON change its behaviour ($Md = 5,\ n = 25$). Participants in either **MP 4, MP 5 or MP 7 (group 2)** rated lower ($Md = 4,\ n = 26$). Participants, who experienced **MP 8 (group 3)**, rated that they hardly saw any change in the behaviour of BIRON when they encountered it ($Md = 1,\ n = 5$). A post-hoc test using Mann-Whitney U tests with Bonferroni correction (alpha=.05/2) revealed a significant difference between group 1 (MP 1, 2, 3, 6) and group 3 (MP 8) (Mann-Whitney U: $z = 7.5$, $p = .002$, $r = .74$). The effect size r reveals that the strength of the difference is large. The answers for question 1 reflect how well the changes in motion of the MPs were visible. Especially, the ratings for MP 8 correspond to the actual behaviour of BIRON in MP 8: Participants who should have seen BIRON driving

[5]The explanation of all statistical tests and notations can be found in the Appendix A in three tables (p. 211 f).

straight towards them, without stop or turn or diagonally driving. This might have also been the reason for the three participants, who did not fill in the questionnaire because they stated that they had not seen BIRON consciously. MP 1, MP 2, MP 3, MP 6 are perceived to have more salient changes in the behaviour. This result hints that motion patterns, which include a pause at the beginning or end are recognised as a change in BIRON's behaviour. Pauses in motion make the motion more abrupt. The abruptness in motion attracts attention cf. Section 2.6. In the case of MP 8 no abruptness in motion can be recognised as BIRON is not changing the direction nor is making any pauses in the motion.

5.3.2 Question 2: Cause-Effect Relationship

Question 2 was asking the participants to rate on the 5-Likert-Scale, whether they think that BIRON had changed its behaviour because of their presence. This question is implicitly asking whether participants attributed a cause-effect relationship to their and BIRON's actions, e.g. BIRON changed its behaviour because of the participant's presence cf. Section 3.1.2.

The analyses for question 2 reveal that no groupings (dynamic and static settings, less and more blocking, defensive and offensive) were significantly different to the corresponding group. Further analyses[6] reveal that there are two groups that differ significantly in ratings for question 2. Participants, who experienced MP 1 - MP 7, think BIRON changed its behaviour because of their presence ($Md = 4;\ n = 43$), whereas participants, who experienced MP 8, do not think that BIRON changed its behaviour ($Md = 2,\ n = 5$) (Mann-Whitney U: $z = 2.56$, $p = .01$, $r = 0.37$ (medium effect)).

This result means that all MPs except MP 8 were attributed with an intention. This question does not record which intention it was. Therefore, further analyses of open questions provide information of the participants' interpretation of robotic motion patterns.

[6] A Kruskal-Wallis test for all MPs was used and as a post hoc tests a range of Mann-Whitney U tests were used with Bonferroni correction for multiple tests alpha=.05/3. Only the relevant test is stated here.

5.3.3 Question 3: Interpreting Intention

Question 3 is asking whether participants can attribute an intention to BIRON's behaviour, participants were asked in an open question what they thought BIRON's intention was, when they spotted BIRON in the corridor.

The free answers can be summarised to three answers:

a) "BIRON is avoiding me",

b) "I have no idea whether BIRON is capable of having intentions on its own"

c) "BIRON is driving with goals of its own (avoiding excluded)",

54 participants out of 56 answered this question. Two participants left the open space free and were not counted. A hypothesis is that the less blocking strategies of the static and the dynamic setting of BIRON should elicit more attribution of an avoiding intention than the other MPs because in the less blocking strategies BIRON moves to the side and makes more room for the participant. This hypothesis cannot be confirmed.

Comparing only the less blocking MPs of the static and the dynamic setting with each other, there is a significant difference in the attribution of intention between the two settings (static, dynamic) and less blocking: [static, less blocking (MP 1 & 3)] x [dynamic, less blocking (MP 5 & 7)] (Fisher's exact test: $value = 7.4$, $p = .02$, $c_{corr} = .75$, $N = 32$)[7]. This means that 70.6% of the participants in MP 1 and MP 3 think BIRON is avoiding them whereas only 26.7% think so in the dynamic setting (MP 5 & 7). In MP 1 & MP 3, 11.8% of the participants think BIRON pursued goals of its own whereas 53.3% of the participants thought so in MP 5 & MP 7. 17.6% of the participants cannot detect any intention of BIRON in MP 1 & MP 3 whereas in MP 5 & MP 7 20% of the participants do not attribute any intention to BIRON. The difference between MP 5 & MP 7 and MP 1 & MP 3 is that BIRON is already moving when the participant saw BIRON in MP 5 & MP 7, whereas in MP 1 & MP 3 BIRON was standing still and then was turning and driving to the side or driving away from the person cf. static and dynamic setting in Figure 5.4 (p.88). This indicates that the pause of motion at the very beginning of the MPs plays a role in attributing an avoiding intention.

[7]The Fisher's exact test is a non-parametric test to explore relationships of a low number of cases in each category [Pallant, 2010]

Figure 5.6: *This filmstrip presents BIRON conveying MP 3 and a participant.*

A Fisher's exact test revealed that, BIRON, which conveyed MP 1, MP 3, and MP 6 was attributed with an intention of avoidance significantly more than in MP 2, MP 4, MP 5, and MP 7, namely, in 75% of the cases in MP 1, in 67% of the cases in MP 3, and in 50% of the cases in MP 6 (Fisher's exact test: $value = 13.9$, $p = .001$, $cc = .47$, $N = 49$). MP 2, MP 4, MP 5, and MP 7 attributed in 50% - 75% of the cases a different intention to BIRON than the avoiding intention cf. Figure 5.8. Exemplary, Figure 5.6 presents a filmstrip of BIRON conveying MP 3 and a participant in her trial. Exemplary, Figure 5.7 presents a filmstrip of BIRON conveying MP 4 and a participant in her trial.

Participants, who experienced MP 8, stated in 40% of the cases that they had no idea of BIRON's intention. This is more than participants of any other MP. This result is conforming to the results from question 1 and 2, suggesting that participants thought that BIRON had not changed its behaviour and they did not associate BIRON's behaviour with their own as frequent participants who experienced different MPs.

The intentions other than 'avoiding' The interpretation of BIRON's intention in the 75% of the cases in which participants, who experienced MP 2, varied from: "the robot wants to guide me", the robot wants to block my way", and "the robot wants to drive to the staircase. The interpretations of MP 4 (any other intention) did not vary a lot. Here, the prevailing interpretations were "BIRON wants to drive along the corridor" and "BIRON wants to block my way." Figure 5.7 presents a filmstrip of BIRON conveying MP 4 and a participant in her trial. The intention, which was attributed to BIRON in MP 5 (not the intention of avoiding) was of the nature of: "BIRON wants to greet me". The intention, which was attributed to BIRON in MP 7 the most, was: "BIRON wants to drive along the corridor".

Figure 5.7: *This figure displays a filmstrip of BIRON conveying MP 4 and a participant in her trial.*

BIRON in MP 6 is attributed with an avoiding intention Not expected was that participants, who experienced MP 6 (dynamic, defensive, more blocking) attributed the intention of avoidance to BIRON in 50% of the cases (25% no idea, 25% own goal) cf. Figure 5.8. Considering the results of question 1 and 2, MP 6 is a salient MP throughout the results of these questions. Furthermore, the duration of MP 6 is significantly shorter ($M = 8$ *sec.*, $SD = 5.1$ *sec.*) compared to the other MPs

(MPs collapsed $M = 15.5$ *sec.*, $SD = 5.9$ *sec.*) (Mann-Whitney U: $z = 2.42$, $p = .02$, $r = .32$ (medium effect), $N = 54$). Another difference to the other MPs is that BIRON in MP 6 stops at the end MP in the middle of the door frame. Participants experienced this stop before they passed the robot in 75% of the cases. This stop took place on average 2.5 seconds ($M = 2.5$ *sec.*, $SD = 2.8$ *sec.*) before participants passed the robot. This is significantly different to all the other MPs (Mann-Whitney U: $z = -2.65$, $p = .004$, $r = .36$ (medium effect), $N = 54$). BIRON in MP 5 stops also at the door frame but it takes longer to drive to the side and position itself at the door frame, therefore BIRON stops on average 1.3 seconds ($SD = 2.7$ *sec.*) after the participants have passed the robot. BIRON in MP 2 finishes the MP on average 1 second ($SD = 2.7$ *sec.*) before the participants overtake it but the execution of MP itself takes longer (BIRON turns around and drives in the same direction as the participant is walking). This analysis presents that participants, who experienced MP 6 had time to perceive a short drive of BIRON and the stop or pause in motion at the end of the MP. Therefore, the motion in MP is considered to be more abrupt compared with the other MPs in the dynamic setting. This result is conforming to the animation principle "exaggeration" which suggest exaggerating the behaviour to make it more legible cf. Section 3.3.1. In addition pauses or in this case a complete halt in motion helps humans to segment actions cf. Section 3.3.1.

5.3.4 Question 4: BIRON should do

Moreover, the participants had to choose what would have they liked BIRON to do, when the robot was already driving towards a narrow passage and when BIRON was already blocking the narrow passage. There is no difference in the response behaviour of the participant across all the MPs. That is why they are presented together in this section. The actual MPs, which participants could experience, serve as the basis for the answers for this question: moving backwards and sideways, moving forward and sideways, straight motions, complete stop in motion. This question also asked the participants to imagine a static setting: the robot is standing still and is blocking a narrow passage and a dynamic setting: the robot is driving towards a narrow passage and towards you.

Static and Dynamic Setting In the dynamic situation participants prefer the robot to drive forward and sideways in 47.3% of cases, whereas participants chose

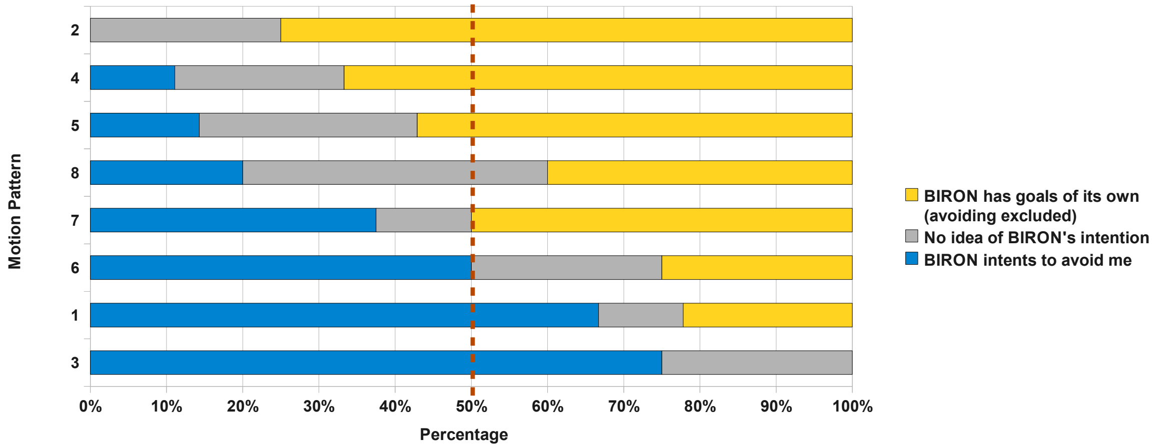

Figure 5.8: *This figure displays a chart with the answers of question 3 per MP. This question asks the participants what they thought BIRON's intention was, when they spotted BIRON in the corridor. The answers are given in percentage for each MP to compare them across all MPs. The answers a summed up into three groups (yellow, grey, blue). Generally, BIRON executing MP 3 was attributed with an avoiding intention more than any other MP (blue). Contrary, MP 2 is not attributed with an avoiding behaviour at all (yellow) but participants believed that BIRON had a different intention. Participants, who experienced MP 8 were mostly not able to attribute any intention to BIRON (grey).*

this possibility in only 9.1% within the static setting. In the static setting, *driving backwards and sideways* is the more preferred way for BIRON to react (54.5%) in a static setting. Contrary to the static setting, the backward and sideways motion in the dynamic setting are chosen only in 40% of the cases. In both situations, straight motions of BIRON were not as preferred. Table 5.5 presents an overview of the ratings for both settings.

Considering the static setting, a robot, which drives backward and sideways and away might be not as intimidating as a robot, which starts its engine to drive forward even if it drives sideways. The timing aspect could also play a role: a participant would pass the robot, which drives backwards and sideways, later in the course of the entire passing situation than a robot which drives towards the person. Furthermore, both interaction partners would have more time to adjust their motions in order to pass by. The difference between 'driving backwards and sideways' and MP 1 is that BIRON is not able to drive backwards. BIRON had to turn around and then drive forwards because BIRON has no omnidirectional sight (e.g. laser scanner with a range of 360°). Therefore, it was not safe for the robot to drive backwards. Considering that BIRON in MP 1 was interpreted to have the intention to avoid the participant, driving directly backwards can add to the legibility of the intention in MP 1, because it faster as turning around, so that participants can perceive the end of the MP before they actually pass the robot. Another way of moving faster would be if BIRON could move in a holonomic manner e.g. directly to the side.

Interesting is that 29.1% liked BIRON not to move at all when they had to imagine the robot standing in a narrow place (static setting). Unfortunately, this such a pattern is not tested. A similar MP can be found in the dynamic setting (MP 6). Although BIRON in MP 6 was already driving and then stopped in the middle of the door frame, participants perceived this behaviour as an avoiding behaviour cf. Section 5.3.3. Generally, a driving robot might be more intimidating than a standing robot, especially, if it does not signal early enough that is not colliding with the participant cf. [Butler and Agah, 2001].

In summary, it can be stated that participants would like to have BIRON drive backwards and sideways in case it is already blocking the path in a narrow passage. Waiting to let the participant pass first can also be a possible strategy. Driving to the side as early as possible is the strategy that is preferred in the dynamic setting. Compared to the actual experienced MPs of the dynamic setting (MP 5 - MP 8) MP 6 (drive and stop), results in a higher rate of attributed intention of avoidances. The reason for that difference between the actual MPs and the response behaviour of the participants might be that BIRON took to long to actually drive to the side in the MPs as the point at which BIRON and the human passed was before the robot actually reached its final position within the MP cf. Section 5.3.3.

	backwards sideways	forward sideways	straight movements	stop
static	54.5%	9.1%	7.3%	29.1%
dynamic	40%	47.3%	1.8%	10.9%

Table 5.5: *These are the results of the questions in which the participants had to choose how they liked BIRON to behave. Two initial situations were considered when they answered the questions: they had to imagine that the robot is already standing in a narrow space (static) and that BIRON is driving towards a narrow passage (dynamic). The possibilities how BIRON should move are given in the top row. Remarkably low rated are the forward movements to the side in the static setting.*

5.3.5 Question 5: Suggestions how BIRON should signal

In an open question participants were asked to write down their own ideas how they would like BIRON to signal that it is going to pass by. Verbal output and any kind of audio signals were suggested in 20% of the cases each. Remarkably, participants suggested putting an indicators on the robot to signal the direction of motion in 60% of the cases. An indicator is a simple but very effective method to tell a person what the robot is going to do - even if the robot is not moving but is preparing to move. Those signs can be seen from further away and enhance the predictability of the interaction. The results correspond to the approach of Matsumaru et al. [2005], who applied an omni-directional display to indicate the robot's speed and direction of travel in a robot follow scenario. Furthermore, Shindev et al. [2012] projects arrows on the floor in front of the robots to indicate its direction of motion.

5.3.6 Question 6: How would a participant signal

In contrast to question 5, this question treats the human way of communicating via motion. The participants should suggest how they would signal the robot that they would want to pass. Table 5.6 displays all recorded answers in a summarised way. Walking sideways was suggested most often (31.8%). Moreover, participants suggested that they could use hand gestures (24.2%). Unfortunately, it is not known whether the participants meant to show, where they want to go or whether they would like to point where the robot should drive. Verbal communication was recommended in 18.2% of the cases.

Additionally, participants had to rate their own behaviour, compared to what they suggested before on a 5-Likert-scale (with 1 being "no did not do what I suggested" to 5 "did what suggested") ($Md = 3,\ SD = 1.6$). In a video analysis, however, 38.2% of the participants actually did what they suggested and the others did not. It is remarkably that nobody actually used speech or any kind of hand signs to tell the robot what he or she was going to do.

Hand signs and speech might be a possibility to interact in those situations but they are definitely not the intuitive way in a passing by situation. This is conforming to Hall's [1966] interpersonal zones: people do not tend to address someone via speech from further away than 3.6 m cf. Section 3.5. Furthermore, Patterson et al. [2002]

reported that pedestrians' patterns of passing each other consist of moving to one side and either smile and nod or ignore each other - Patterson et al. [2002] did not report that humans use hand signs. This finding suggests that the participants were not able to recall their way of signalling BIRON.

Answer	*Percentage*
walking sideways	31.8%
hand gesture	24.2%
speech	18.2%
progressing	6.1%
orienting the body away	6.1%
waiting	4.6%
normal behaviour	3.0%
touching	1.5%
going away	1.5%
walking slowly	1.5%
eye contact	1.5%

Table 5.6: *This is the summary of answers of an open question. In this question the participants were asked to think of ways to show the robot that their intention is to pass by in the particular situation they experienced. The first column contains actions the participants would prefer.*

5.3.7 Summarising Discussion

In summary, the participants would like to have more possibilities for BIRON to signal, what it is going to do. They also like BIRON to drive sideways either backwards or forward depending on the situation. Differences between an already moving robot and a standing robot even if it is the same narrow passage and avoiding route were found. Results suggest that a robot that is blocking a narrow passage should move backwards and not towards the approaching human even if this motion would be an avoiding motion. These suggestions are not so easily implementable on BIRON: backwards motions are not safe as BIRON has not a 360° vision; motions to the side are only possible while driving forward or after turning around as BIRON has only a differential drive. These might be the reasons why BIRON in the actual MP 3 (driving forward and sideways) was attributed to have the intention to avoid the participants slightly more than in the MP 1 (turning and driving forward and sideways). Even if the motion of BIRON was away from the participant in MP 1, MP 1 took longer to be executed than MP 3. Thus the participants had to wait longer to figure out what BIRON's goals were.

Keeping motionless is another possibility participants liked BIRON to behave in a static blocking and passing situation. This conforms to the safety breaches, Hüttenrauch et al. [2009] reported. Hüttenrauch et al. [2009] reported that participants, who encountered a robot, which blocked a narrow passage, squeezed around the robot. Generally people had no anxiety to come close to the robot for a certain amount of time and especially when the robot was not moving, people squeezed around it. However, it is discussable whether or not the strategy of humans squeezing around and robots blocking narrow passages should be the general strategy for those situations. Of course, these strategies only work when there is enough space to squeeze around. Concerning this, Koay et al. [2009, p.224] summarise their results of analysing initial robot encounters of a HRI study: "The main finding from that study indicate that participants dislike the robot blocking their path, moving behind them, or [moving] on a collision path towards them. Broadly, these can all be classified as the participants' safety concerns." Considering the results of this study it is remarkable that participants, who actually experienced a robot driving towards a door frame and towards them and then stopping in the door frame, interpret this behaviour as avoiding behaviour (MP 6). However, this strategy was not frequently suggested by the participants when they had to imagine such a situation. Furthermore, participants suggested verbal interaction but in the actual trials motion was the prevailing means of communication. In addition participants suggested putting indicators on the robot to signal the direction of motion of the robot. Participants can imagine several ways to communicate their intention to BIRON but only a few participants acted as they suggested during the actual study which suggest that they acted without consciously thinking about it during the study.

The results of the actual interpretation of the MPs suggest that participants need to have any indication how to segment the robot's action and make sense out it. Pauses of motion at the beginning of a MP and at the end facilitate the segmentation of actions cf. Section 2.6 and therefore the interpretation of motion as causal chain of events cf. Section 3.1.1 - 3.1.2. Especially, MP 1, MP 3 and MP 6 implement these halts in motion. Therefore, powerful characteristics of motion, which enhance the interpretation of whole-body motions, are the pauses around the motion and other means by which the motion can be segmented in meaningful events that participants can associate with their own actions.

Observations: Timing of actions

The observational study with its eight different behaviours displayed by BIRON brought some insight into how important the timing between the manoeuvres of the robot and the humans walking velocity (average 1 m/s) is. Assuming that a person is detected on average at a distance of 6 m, a robot has 6 seconds to decide in which situation the robot is in and what strategy to apply till the person would reach the robot. This calculation only works if the robot is standing still. This conforms to the wish of the participants that the robot should drive backwards and drive away instead of starting to drive towards the person if it is already standing still cf. Table 5.5. With this manoeuvre the robot obtains more time to display its goal. This finding is also conforming to outcomes reported by Takayama et al. [2011]. The authors found that the timing for conveying body language was the crucial part in succeeding to design expressive motions for their animated robots. Moreover, Ducourant et al. [2005] explain that humans need to plan not only their own actions, they have to consider the actions of others as well, when planning their own actions. Timing is important within the planning of one's own action, especially regarding the amount of space, and interaction partners, they have to manage [Ducourant et al., 2005]. Furthermore, the Gestalt Principle, temporal succession, describes that succeeding actions are easily interpreted to have an effect-cause relationship. That means it is broadly assumed while interpreting events (actions, motions) that nothing happens without a reason [Katz and Metzger, 1969]. Combining this principle with the information that the timing of events (motions) is important to predict actions of others, this emphasises even more the role of timing of motions or motion patterns in HRI. In the worst case the human would assume that motions of the robot have a different effect-cause relationship as they originally were planned to have, e.g., human who could easily interpret the motion of a robot which moving towards oneself as an impolite act into that not as a part of an avoiding manoeuvre which is initiated too late.

In particular, the notion that humans interpret motions of the interaction partner no matter whether or not they were intended, when regarding that the robot perception is not 100% free of errors [Lohse and Hanheide, 2008] so that the robot might stop in its motion for no other reason than to cope with the erroneous readings. For example, a situation might occur, that a robot is driving from one place to another, then stops midway and starts driving again. This situation might be interpreted by a roboticist in this way: "the robot's laser range finder sent wrong data and module

for navigation detected a obstacle so that the robot stopped to plan a new path and as the laser range finder sent better data the obstacle was resolved and the robot's navigation module continued the new/ old plan". Whereas a human, who is only using / interacting with the robot without expert knowledge, might interpret the situation in a completely different way, e.g., the human could think that the robot forgot the commands of the human or the robot is waiting for the human to pass by, which again could prompt the human to instruct the robot again or walk in a direction the robot did not predict. A challenge, which was encountered during the study, was that, the obstacle avoidance of the robot needed to be adjusted as the robot had the task to drive along the wall as close as possible during some MPs. On the one hand, a robot should stay away from any kind of obstacle as far as possible. On the other hand, it should also drive as close as possible to a wall and along it when there is a narrow passage and a human is about to pass by. This controversy need to be considered when operating a robot in narrow spaces vs. open spaces as the robot needs to decide, especially in narrow spaces when and which "obstacle" needs more space.
Regarding that Clarkson and Arkin [2007, p.46] proposed in a range of heuristics for evaluation of robots that the a robot should "help users recognize, diagnose, and recover from errors, future error recovery systems should take the information into account that these small abrupt motions will be interpreted and need to be explained as these motions might trigger new problems within the smooth interaction between the robot and the human. Therefore, a robotic error recovery systems should be equipped with a module or sensor which monitors the motions of the robot, whenever errors occur that resulted in robotic abrupt motions (e.g. stop and go motions) accidentally, the system needs to explain somehow what these abrupt motions meant. These explanations do not need to be via spoken words, as suggested by the participants of this study the robot could use an indicator as drivers in cars use, to indicate the direction it is going.

5.4 Preliminary Analysis of Single Motion Intervals

In this study the observation and analysis of human whole-body motion has only a minor position. However, the human - and the robotic whole-body motion were video annotated by two student assistants. Section 5.1.6 presents how it was annotated. The agreement of the student assistants on the annotations was computed with the Cohen's

Kappa[8] [Cohen, 1968]. The Cohen's Kappa, which corrects for chance agreement, ranges between 0.76 -0.81. According to Bakeman and Gottman [1986], these values are considered to be a good to excellent agreement of the coders' [cited in Benigno et al., 2007, p.180].

Small whole-body motions, which are conforming to the small adjusting steps reported by Hüttenrauch et al. [2006b] and others cf. Chapter 3 can be observed 1-2 times in 20.4% of participants at one stage of their trial. These steps are either to the side or to the front and are executed at a distance of on average 1.2 m (SD = 0.81 m). It is remarkable that 82.4% of these steps are accompanied with a change in the velocity at the beginning of the step. Furthermore, in 57.1% of the velocity changes, a pause in motion occurred before the step. The velocity changes, especially, the pauses before the steps make the motions more abrupt and therefore would when displayed to a human interaction partner attract attention. Moreover, these whole-body motion intervals occur in 90.1% of the cases at the same time as the robot BIRON drives in the middle of the corridor or is already driving in the middle. These findings are mentionable because they illustrate that the participants use small motions in an abrupt way to coordinate themselves with the robot. These steps, limited by the pauses or changes in velocity are also conforming to the definition of motionings given in Chapter 2.6 if they are performed to spatially influence the robot. This statement is however discussable as the study did not measure physiological data to interpret the internal processes in the human. Even if the message behind this behaviour is not known in detail yet it is safe to assume that this behaviour was conveyed to spatially coordinate with the robot as it deviates from "normal" behaviour of humans passing by without the challenge of a robot blocking the path [Patterson et al., 2002; Kirby, 2010].

The analysis of human and robot motion in interaction with each on basis of the video annotations in this study is presented in Chapter 8 as it new ongoing research on the basis of my entire thesis. The idea here is to analyse the human and robot motions in interaction with each other by expressing the video annotations in the form of the QTC_c cf. Chapter 3.4.3. A general result of this analysis indicate that the participants display for each robotic motion pattern a different motion pattern of their own, resulting in distinct motion sequences of QTC_c relations [Hanheide et al., 2012].

[8]"The kappa coefficient, the proportion of agreement corrected for chance between two judges assigning cases to a set of k categories, is offered as a measure of reliability" so Cohen [1968, p.213]. It is based on a weighted χ^2 function.

More information on the analysis of the whole-body motion of the human and robot via QTC_c is described in Section 8.1. However, the key message from this analysis for this section is that the findings support the hypothesis that the participants of this study try to spatially coordinate each other with the robot and its different displayed motions, in particular when the robot is blocking the path for the participant to proceed. To have a closer look at the communicative whole-body motions of humans in interaction with the robot, a new study is conducted. The next investigation should explicitly provide a situation in which a participant needs to spatially coordinate with the robot to pass by.

5.5 Limitations and Advice for the Study on Human Motionings

With the observations and discussions in mind the study on human motionings is planned to investigate human communicative whole-body motions in a similar situation as presented in this chapter. Regarding the discussion about timing, the robot is going to have a more static role in blocking the path for the participants. This guarantees that timing of the robot motions is somewhat controlled as the robot is standing still during the time of the observations of human communicative whole-body motions. The next study focuses only on the way people naturally interact with a robot in a passing by situation, in which a robot blocks the path accidentally cf. Chapter 6. The blocking robot provides a reason for the participants to spatially coordinate with the robot. This statement is derived from the preliminary analysis of human and robot motions as motions which fit into the definition of motionings occurred whenever the robot was moving in the middle of the corridor thus blocking the path for the participants. Moreover, fewer robotic motion patterns have the advantage that the participant's whole-body motions are not only comparable on a broad level but also comparable on a fine-grained level. Furthermore, the next study is focussing on the actual interaction situation because the study on robotic motion patterns focused on passers-by which were not used to the robot. This might influenced the conveyed human motions as the robot presence might have been unexpected for the participants even if there were signs telling them that they might encounter a robot and even if they were recruited to take part in a HRI study.

Chapter 6

Investigating Human Motionings

Human motionings in HRI are investigated in this chapter. The overall purpose of this thesis is to investigate the communicative potential of whole-body motions in HRI. The methodology of this thesis is to investigate both, the robot role of conveying motion and the human role of conveying motion as part of the nonverbal communication in interaction with each other. This chapter provides information about *the human role or perspective of conveying communicative whole-body motions in interaction with the mobile office robot Snoopy.* Figure 6.1 displays an overview of the thesis' structure and the placement of this chapter within the overall structure.

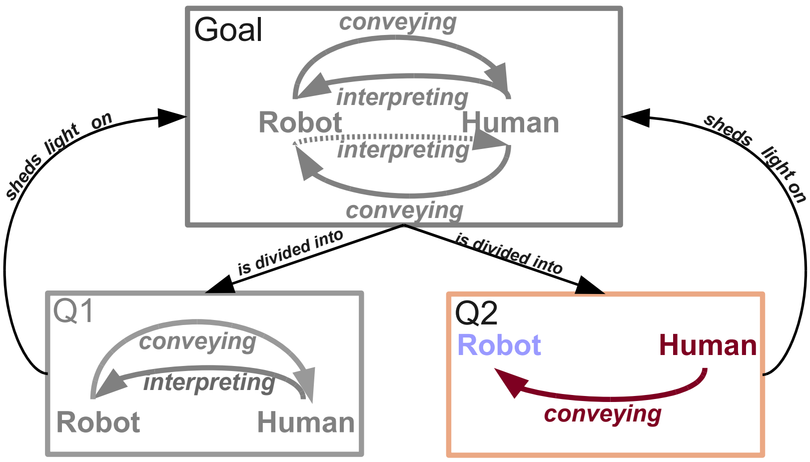

Figure 6.1: *This chapter is about the investigation of human motionings. This investigation is displayed by the lower corner on the right-hand side of this figure. The human role of conveying communicative whole-body motions in a spatial coordination situation with the robot Snoopy is in the focus of this chapter.*

Investigating the human role of conveying motionings in HRI is important because human communicative whole-body motions are an inherent part of the human nonverbal communication. It is stated and being researched by various researchers that humans use nonverbal means of communication when interacting with robots [Breazeal and Fitzpatrick, 2000; Dautenhahn, 2007a; Takayama and Pantofaru, 2009] and cf. Chapter 3. The HRI community has recently started to investigate human *natural* nonverbal communication in HRI setups as humans use, of course, human nonverbal communication whether or not they are asked to make use of nonverbal means [Kanda, 2010]. Human motionings are defined as part of the natural human nonverbal communication towards robots in Section 2.6. The hypothesis is that these motionings are conveyed by humans as communicative means to spatially coordinate with the robot. This hypothesis is supported by Hüttenrauch et al. [2006b] who report on, small whole-body motions from humans towards a robot and suggest that these have a communicative purpose. The contribution of this chapter is to enrich the definition of motionings on a detailed basis by reporting on the findings of this study. This is important for discussing the potential of communicative whole-body motions with the goal in mind that on the one hand future robotic systems should be able to represent and detect motionings in various situations and on the other hand to get ideas how design robotic motionings.

Therefore, the guiding question for this chapter's investigations is
Q2: *Which characteristics or motion patterns of human whole-body motion are relevant for conveying intention towards a robot? What, in the human whole-body motion, conveys the information to predict the actions or intentions upon which a robot should act? It is also the question of how to find, define and describe human communicative whole-body motion for a robotic system to interpret?*

To shed light on these questions (Q2) a study was designed which needs to fulfil the following requirements: These requirements result from the preliminary definition of motionings (Section 2.6) and the lessons learned from the conducting the study on Robotic Motion Patterns (RMP) which is described in Chapter 5.3.7. The general requirement of this thesis is: the conveyed motions should be *natural*. This means that the observed whole-body motions need to be conveyed in spontaneous way without the knowledge that communication via body language towards the robot is possible and what the goal of the investigation is. Furthermore, the robot is not allowed to be responsive (when steered by a confederate experimenter) to any kind communicative whole-body motions because this ability could trigger motionings.

A requirement, which is derived from the analysis of the RMP study is: fewer conditions make the data more comparable on a structural level. Regarding the comparability between data the timing problem of succeeding motions of the human and the robot needs to be considered: Less motion or no motion of the robot reduces or rules out timing issues. Furthermore, participants in the study need to have an active role in interacting with the robot to provide possibilities for the participant to communicate via whole-body motion i.e. spatially coordinate with the interaction partner. The study needs to conform to the initial situation: the robot obstructs the passage accidentally for a human to continue her way. The participants need be become familiar with the basic usage of a robot, to rule out any behaviour that occurred due to uncertainty of the participant not knowing whether or not the robot can be used for interaction.

Outline of this Chapter In the course of this chapter, the observational case study is described, which is conducted to observe on human motionings towards a robot and to fulfil all the requirements. The data of the study are analysed and discussed in several sections. However, there are four core sections of data analysis conducted to advance the definition of motionings.

- The coding scheme for motionings is created in Section 6.3. This section is the initial point of all analyses of characteristics of human motionings.
- Section 6.4 analyses the temporal characteristics of the motionings: duration, pause duration, the frequency of motionings and the analyses of the conditions *less blocking* and *more blocking* presented in this chapter.
- Section 6.5 presents a detailed analysis of the characteristics of motionings: orientation, position, distance and direction of motion (trajectories). The values are represented by a relative and qualitative framework. This analysis is also conducted to verify the coding scheme by computing whether or not the characteristics form any patterns that match the categories in the coding scheme.
- The motionings, which were identified, are compared to other motionings in other situations of the observational case study (guiding, presenting episodes). The comparison to other motioning intervals is conducted to check the validity of the coding scheme and the corresponding characteristics. Furthermore this section provides information of how to advance the coding scheme.

6.1 Observational Case Study on Human Motionings

To fulfil the requirements for this study and to comply with the initial situation an observational case study was conducted at Lund University (Lunds Tekniska Högskola), Sweden[1] that provides information on how humans manage interpersonal space on a narrow door sill. Therefore, a scenario was invented that includes a situation in which a participant has to spatially coordinate with the robot that unintentionally blocks the path for the participant at a door frame. The aim is to observe natural human motionings towards a robot. This situation was embedded in a cover story to ensure that participants do not feel awkward or uncomfortable. For that reason also, participants were introduced to the robot and its way of driving and speaking so that motions of the participant would not be about an awkward or uncomfortable situation. To meet these requirements the situation is embedded in an office tour scenario similar to the home tour scenario which Hüttenrauch et al. [2009] reported: In a field study, the authors brought the mechanoid robot Minnie to people's houses and flats. The participants had to guide the robot through their houses to show rooms and items. In this context, Hüttenrauch et al. [2009] reported on blocking situations that occurred naturally at narrow passages. In the study reported in this chapter, participants had to guide the robot Snoopy into three rooms in an office environment: from a corridor into an office, a printer room and a meeting room. Figure 6.2 displays a sketch of the floor plan and the paths the participant had to take in order to present the room and items in the room. To create a narrow passage and to observe human motionings in spatial coordination situations, the narrow room (printer room) with a narrow door frame was part of the office tour. The cover story for the participants provides a reason why the participants should guide the robot around, go from one room into another room with the robot and manoeuvre themselves accidentally into a blocking situation with the robot. The focus is on analysing human motionings via video data afterwards.

6.1.1 Cover Story and Task of the Participants

Participants were invited to meet our robot Snoopy. Their task was to guide the robot Snoopy around an office environment. All participants heard the same cover

[1] The study was conducted in cooperation with Dr. Elin Anna Topp, http://cs.lth.se/elin_anna_topp/.

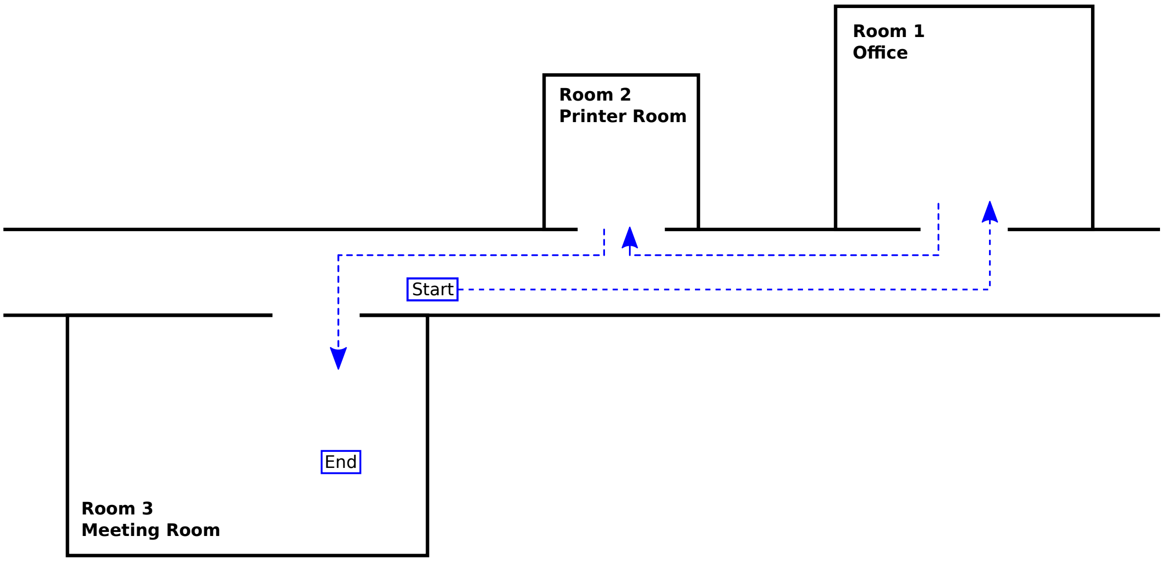

Figure 6.2: *This figure displays a sketch of the floor plan in the office building in which the office tour took place. The blue dashed lines present a sketch of the path and order of the rooms the participant had to walk guiding the robot and teaching rooms and items in the rooms to the robot.*

story: They were invited to imagine that this robot was their new office robot, which needed a first tour around the office. In order to help them afterwards, Snoopy needed to know, where the rooms were and items in the room, e.g., where the printer room was, and where paper and the printer were. Similar cover stories for home tour scenarios are reported by Hüttenrauch et al. [2006b, 2009]; Spexard et al. [2007]; Lohse [2010]. Participants were asked to show three rooms and were asked to freely choose items in the room to show to the robot. An office, a printer room and a meeting room had to be presented in that order to the robot. Each trial was 15-20 min. depending on the participants' imagination to show items in the rooms to the robot. An experimenter provided a sheet of paper with verbal commands for the participants to navigate and present items and rooms to the robot, e.g., 'forward', 'backward', 'left', 'right', 'follow',and 'this is a ...'. Participants were also allowed to use different wordings of these commands to navigate the robot, e.g., 'go forward', 'drive backwards', and 'follow me'. This was done to keep the participants from over thinking the exact commands, which distract the participants from continuously interacting with the robot. For that reason a short practise trial in the corridor with the participant was conducted to practise the commands and get used to Snoopy's behaviour. Furthermore, the participants were not allowed to keep the paper with the commands during their trial. Of course, the participants were not informed of the underlying question on nonverbal communication.

This cover story was invented to distract participants from the goal of the study, to keep awkwardness and uncomfortable feelings on a low level, and to comply with a typical interaction scenario in HRI.

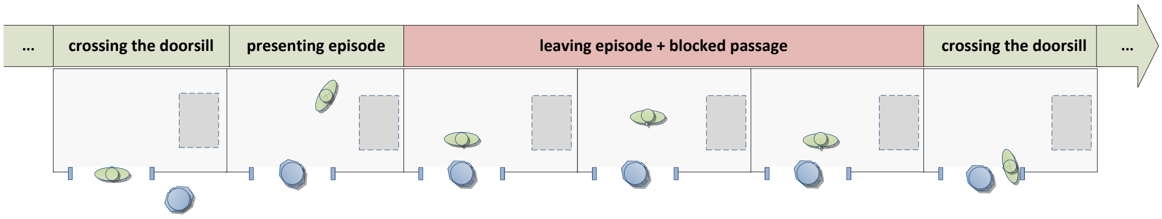

Figure 6.3: *This figure displays the important segment of the study. The participant goes to the printer room and commands the robot to follow and eventually crosses the doorsill, positions the robot and presents the printer room, the paper, and the printer to the robot (crossing the doorsill, presenting episode). Subsequently, the leaving episode follows (marked in red), which is the time interval after the last item has been presented and continuously walking out of the room. In the leaving episode the participant encounters the robot which blocks the way out of the room. During the leaving episode participants are expected to motion the robot that they would like to leave the room before they actually leave the room. The printer room was the participants' second room to show. So that one room was left to guide the robot to.*

6.1.2 Experimenter and Wizard Operator

The experimenter was also the wizard operator, who was not only monitoring the robot in vicinity (3 - 5 m), but also summarised and forwarded the verbal commands of the participant to the robot via a wireless connection, e.g., the participant would say: "This is an printer", the experimenter would forward the object category (here a workplace) and the name (here a printer) to the robot. The robot would then answer: “stored new workplace printer”. The wizard operator neither went into the printer room nor was visible for the participant in the printer room[2]. Furthermore, a second experimenter filmed each trial with an external camera for later video analysis.

6.1.3 The Robot Snoopy

The robot *Snoopy*, which was used for this study, is a mechanoid and wheeled Pioneer P3-DX platform from Adept MobileRobots, cf. Section 2.2. Figure 6.4 dis-

[2]The wizard operator was visible in the meeting room and in the corridor.

plays Snoopy equipped with two laser range finders (one pointing forward, the other backward) at about 40 cm of height, providing data in an angle of 270° each, thus covering the 360° of the robot's surroundings. The laser data was used for leg pattern based user detection and tracking, as well as for localisation, mapping and navigation purposes. A small Netbook was additionally mounted on the robot to decrease the workload on the robot's on-board PC and to provide the speech output. The wooden plate carrying the laptop was attached to an aluminium bar construction that gave the robot a taller appearance (about 1.3 m of height). A video camera was mounted on the top of this construction to record the robot's perspective and to provide an idea of Snoopy's front and back to participants. The Snoopy is equipped with a differential drive. Thus, it is able to drive in the direction it is facing (and backwards) and turn on the spot but not directly to the side (without having turned in that direction before).

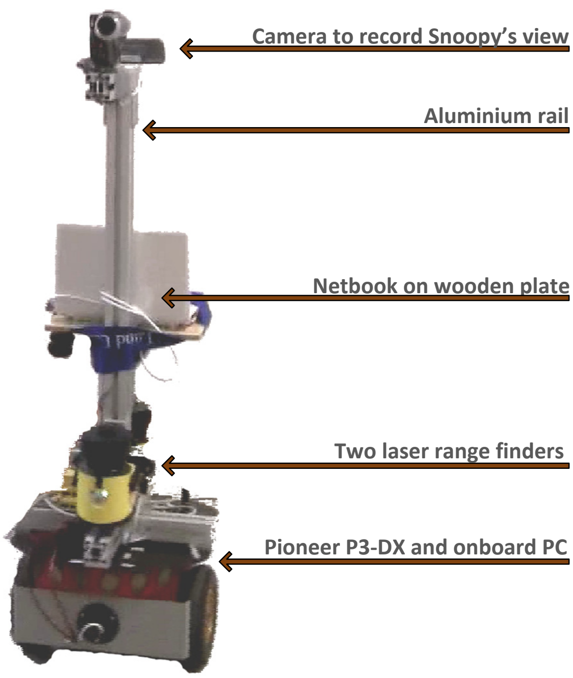

Figure 6.4: *The picture depicts the robot Snoopy, a P3-DX Pioneer platform with an aluminium rail on top to make it taller, put the camera on top and to stop participants to step over it. The camera on top was important to provide a front and back of the robot and give a reference point to the participants where to show items to the robot. Two laser range finders with each* 270° *provide data for* 360° *of leg pattern based tracking of persons, to provide data for mapping the environment, and to provide data for navigation. On-board PC and Netbook are connected via cable. The Netbook is also connected via wireless connection to another laptop which was used to monitor the robots behaviour.*

Software:

For this study, the software framework Human Augmented Mapping (HAM) was used [Topp, 2008]. This version of HAM was designed for guided tour scenarios and is used on other robots [Hüttenrauch et al., 2009]. HAM framework includes autonomously navigation, tracking and following persons. In addition regions (rooms), locations (places) and objects (items) could be taught and reacted according to the HAM model to those taught spatial entities. A Festival[3] text-to-speech server was used to give the verbal feedback to the participant. The utterances were partially pre-coded and completed according to the information given to the robot. No speech recognition was running on the robot as we had participants with different accents in English and wanted to ensure a smooth interaction through the verbal channel. The speech recognition was replaced by the wizard operator.

6.1.4 Leaving Episode at a Narrow Door Frame

This study is an observational case study to provide insight on the case of human motionings in narrow passages in which the robot is blocking the way out of the room accidentally. This situation provides reasons for the human to spatially coordinate with the robot. The situation was implemented in the printer room. Due to the narrow dimensions of this room, it was possible to position the robot in the door frame to observe the room and items in the room and to block the way at the same time. The wooden doorsill of the printer room was on the one hand a natural barrier as the door sill was a bump on the floor but on the other hand was not too high so that the robot could have gone into the room if the participant commanded it to drive. Figure 6.3 sketches the visit of the printer room episode in detail: The printer room was the second room to guide the robot to. This ensured that the participants had, next to a short practise period, the first room as another period to get used to the robot and its way of moving and talking. Furthermore, having a third room to go to afterwards guaranteed that all participants had to / wanted to leave the room in order to show the next room.

To observe motionings for a special situation, it had to be insured that the participants encountered such a situation. As the situation in which participants encountered the

[3]http://www.cstr.ed.ac.uk/projects/festival/, last retrieved April 2012

blocked passage had to be as natural as possible, the participants navigated the robot through their commands all the time without help of the wizard operator. This was also true for the printer room. The participants steered the robot through their commands to and into the rooms themselves and decided themselves where to park the robot to show rooms and items in the rooms.

Due to the narrow dimensions of the room (1.07 m depth x 2.25 m width) the robot was navigated onto and in front of the doorsill of the printer room by the participants in order to present the room and items in the room. At that point the wizard operator made inconspicuously sure that only two different positions to park the robot were possible, e.g., the experimenter slightly delayed the participant's 'stop command' to the robot. Furthermore, the experimenter would, for example, stop 'the turning of the robot' and 'the follow command' in the way that only two different positions of the robot were the result. These positions of the robot form the two conditions of a blocking robot which the participants encountered in the printer room cf. Section 6.1.5. After the participants presented the printer room, the paper, and the printer to the robot, the participants wanted to leave / had to leave the printer room in order to show the next room to the robot. At this point, the robot was still blocking the path for the participant to proceed to the other room. And at this point, human motionings are expected to occur which the participants conveyed to spatially coordinate themselves with the robot. It is also expected that the participants had the goal 'to leave the room' which would make the motionings goal directed. The expectations are supported by Hüttenrauch et al. [2006b], who observed small whole-body motions between "showing-items-to-the-robot" and "the-robot-is-following" episodes in their HRI study. They called the episode, in which they observed these motions, transition episode. Hüttenrauch et al. [2006b] suggest that these small motions, in particular, steps, are hints to a new action episode. The focus of this chapter's investigation is on human whole-body motions in the tiny printer room after the last item in this room was presented to robot until the participants crossed the door sill. As the participants wanted to leave the room and had to find a solution for the blocked passage first, the time interval in focus is called *leaving episode* instead of transition episode cf. Figure 6.3.

The leaving episode is a created and controllable but natural situation of a blocked narrow passage, which is similar to the narrow passages, Hüttenrauch et al. [2009] reported to occur naturally in people's homes while guiding the robot through narrow passages.

6.1.5 Two Conditions: less blocking and more blocking

Due to the narrow dimensions of the printer room, it was possible to plan two conditions to take place without much adjustment or losses of comparability of the participants' data. The participants stopped the robot on the door sill anyway to position the robot in a way that the robot could record the printer with its camera. There was about $1.6m^2$ of space in the printer room to move and a 1 m broad door frame cf. Figure 6.5.

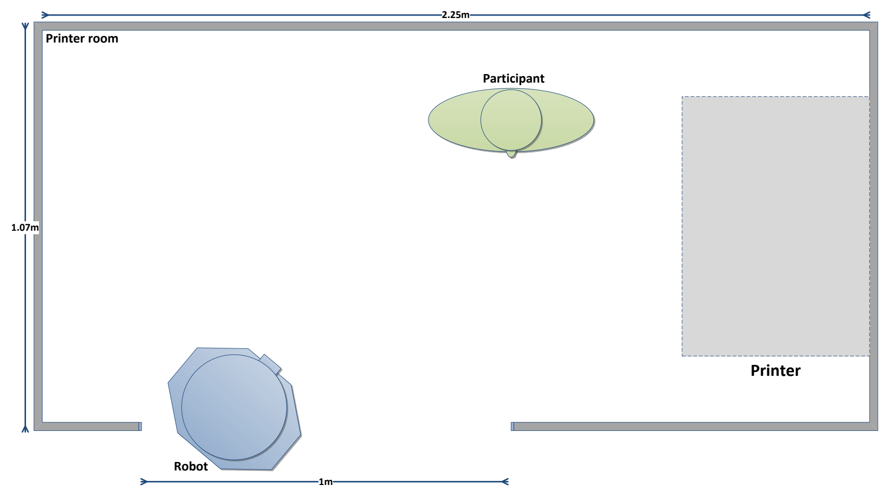

Figure 6.5: *This figure presents the condition:* `less blocking`*. The robot was steered by the participants' commands to this particular position. The wizard operator only corrected minor positioning problems unobtrusively. The dimensions are true to scale. The participants in the room had about 1.07 m in depth and 1.60 m width to move around the room. Apart from the printer, paper in the printer and a bookshelf hanging over the printer, this room was empty. In the less blocking condition, the positioning of the robot left 50 - 55 cm of the doorway free for the participant to move out of the room on the left side (participant's point of view).*

The robot was positioned in a *more blocking* position in the middle of the doorway and a *less blocking* position on the left side in the doorway. The more blocking position left 20 - 25 cm of free space on each side of the robot in the doorway. The less blocking position left 50 - 55 cm of free space on the left side of the robot in the doorway. Figure 6.6 presents a picture in which the robot is blocking the way out for a participant, who had finished showing the room. Figure 6.5 displays the dimensions and setup of the room and the approximate position of the participants, printer and robot in the less blocking condition. Both conditions do not leave a lot of space for the participants to proceed their way.

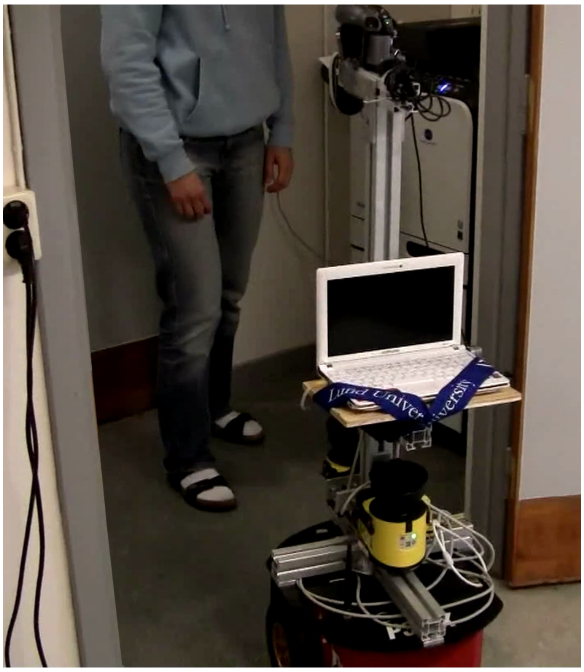

Figure 6.6: *This picture displays the condition:* `more blocking`. *The participants told the robot to follow into the room. They stopped the robot approximately in the middle of the doorway. A wizard operator adjusted the robot's position slightly to achieve more comparability between participants. For example if the participants command the robot to follow and turn to the printer, the experimenter would then turn and follow in the way that the position and orientation was comparable. Due to the narrow dimensions, there was hardly any variance between the positions. The* `more blocking` *condition left 20 - 25 cm of free space on each side of the robot to the door frame.*

The conditions were implemented in this way to observe whether the expected whole-body motions differ in any way and if they only occur when a robot is fully blocking the way. Furthermore, it seemed to be the preferred choice of the participants to park the robot in those ways. These choices were figured out through a small preliminary study which was conducted in Germany alongside a HRI home tour study which is described by Lohse [2011]. Instead of a printer room participants visited a small kitchen with the robot BIRON and parked the robot in similar positions at the door frame to show items to the robot.

Because the aim is to observe natural motionings of the participants' only trials in which the wizard operator was able to position the robot unobtrusively were taken into consideration. The participants were not primed to go into the printer room with the robot in that order. Therefore, only trials in which the participant went into the printer room first and commanded the robot to follow afterwards and stopped the robot close to the door sill were taken into consideration and adjusted by the wizard operator.

6.2 Demographic Results

32 participants took part in the observational case study on motionings from humans toward a robot. The data of four participants is excluded from further analysis because they forgot to show the printer room or did not go into the printer room or the robot was steered in first. This leaves 28 participants (36% female, 64% male, age: $M = 29$, $SD = 8.21$) for motioning analysis[4]. The participants were recruited on Lund University campus (Sweden) resulting in a group of higher educated students and scientific staff from the field of technical science (77.7%), cultural science (15.2%) and economics (7.1%). None of them had seen this robot before or had interacted with this kind of mechanoid and mobile robot before. Although, most participant came from the field of technical science, the self-rated value 'experience interacting with robots' was low ($Md = 2$) on a 5-Likert-scale with 1 being no interaction experience to 5 being expert in interacting with robots. All participants were fluent in English ($Md = 4$) on a self-evaluation on a 5-Likert-scale ranging from no English knowledge 1 - 5 fluent like a native speaker.

[4]The explanation of all mathematical notations can be found in the Appendix A in three tables (p. 211 f).

6.3 Creating a Coding Scheme for Motionings

This section presents a coding scheme for motionings in the leaving episode. The *leaving episode* is defined as the time after the last item has been presented to the robot by the participant and before the participants had started to walk out of the room continuously cf. Section 6.1.4 and Figure 6.7. The aim is to analyse the whole-body motions of participants in the leaving episode in the printer room. Therefore, the whole-body motions in the leaving episode were annotated based on the videos the Snoopy recorded with its camera and the video recorded by the experimenter. To do so a coding scheme had to be created that could be used to identify whole-body motions. To do so the leaving episode had to be segmented into intervals containing whole-body motion. For this segmentation, the start and the end of a motion interval needs to be defined. Motion intervals are defined as a continuous execution of motion without pause even if this pause is just a short hesitation cf. Section 2.6 for a longer definition. As a consequence of the definition, the segmented motion intervals differ from continuously walking out of the room. All motion intervals were excluded which belonged temporally and causally to crossing the doorsill or presenting the room, e.g., putting an item back to its place would be causally connected to presenting, because this motion would serve the goal of putting back the item. Temporally connected are all motions which are not separated by a pause in motion of the entire body from presenting (e.g. showing paper to the robot and putting back the paper) or continuously walking out and crossing the doorsill.

To create a coding scheme, the whole-body motion intervals were annotated in natural language descriptions by two student assistants, who were not informed about the underlying question. The essential summary of these descriptions was that participants had moved their entire body through footsteps, and body weight shifts. On the basis of the descriptions and iteratively demanding more detailed natural language descriptions for footsteps, body rotation, and body swaying, a coding scheme defining different footsteps and body weight shifts was created. Twelve types of motion were identified which cover footsteps and body weight shifts (sways). These body weight shifts are named sways or swaying.

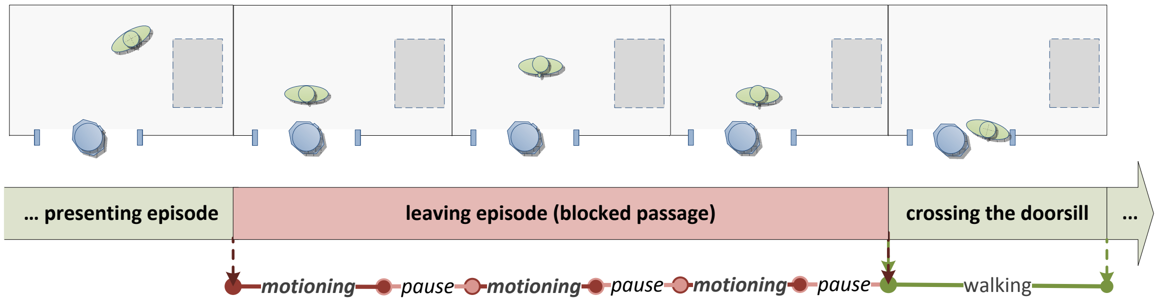

Figure 6.7: *This figure portrays a zoom into the leaving episode. The zoom illustrates exemplary when the motionings investigated in this section occur. Motions like presenting items or walking out of the room are not considered as motioning.*

6.3.1 The Coding Scheme for Motionings

The 12 categories describe the entire range of observed whole-body motions and their exact execution seen in the leaving episode. Three Figures 6.8 - 6.11 display these motions by means of footsteps which move forward, sideways and backwards. These 12 categories form the coding scheme on the basis of which the whole-body motion intervals were annotated. To group the categories into similar step or sway patterns, the 12 categories were divided into five main categories with 2-3 subcategories. The main categories are step, sidestep, sway, sidesway and step-back. Basically, these categories describe motions in different directions: forward, sideward, and backward. Subsequently the main categories are presented:

Step

A *step* consist of two kinds of steps. Generally it is a forwards motion in respect of the moving body. **Step_1** is a motion with one foot forward, consisting of lifting one foot of the ground and putting it down diagonally in front of the other. The feet remain in this position. **Step_2** consists of a step_1 and the motion of the other foot next to the foot, which was moved first. Figure 6.8 displays step_1 and step_2.

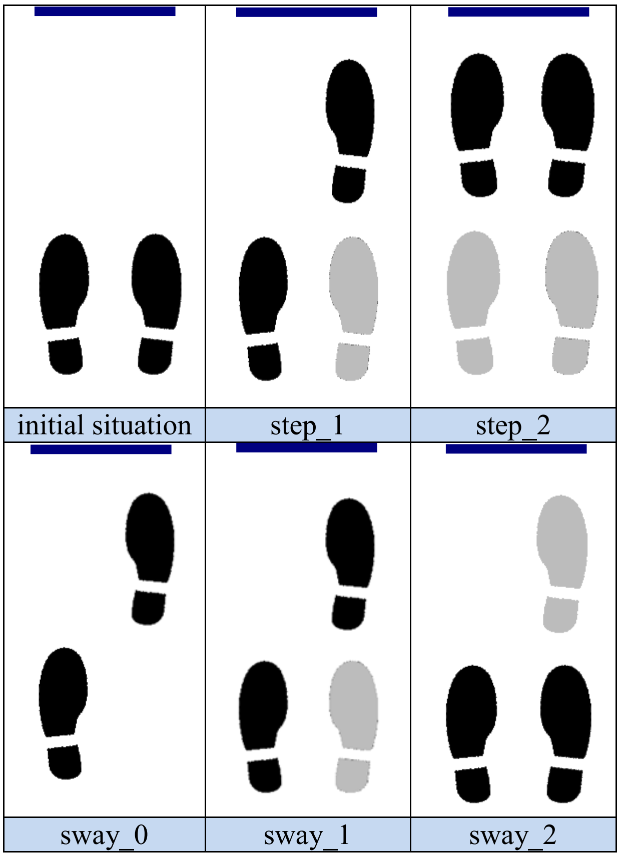

Figure 6.8: *The black footprints depict the actual place of the feet of the participant in each box after the motion ended. A grey footprint stands for a position which a foot had, before it ended at a position depicted by a black footprint. Except* `sway_0`*, all motions start with the initial position in which both feet are placed next to each other. The direction of these depicted motions is always towards an imaginary robot. A blue bar marks the direction in which the robot can be expected cf. Figure 6.6 presents a picture of the robot and the participant. A* `step_1` *consists of a motion with the right leg from the grey footprint to the black footprint in front of the other. A* `step_2` *consists of a step_1 and additionally it consists of a motion with the remaining foot to the front. All swaying motions have also a body weight shift in the direction of motion, which is not depicted. Step_1 and* `sway_1` *differ only in the body weight shifting. Sway_2 differs from step_2.* `Sway_2` *includes a step_1, a body weight shift to the front and a motion with the front leg back to the initial position.*

Sway

A *sway* is segmented into three motions. Similar to step a sway motion is a forward motion in respect to the own moving body and a weight displacement to the front of the body. The motioning **sway_0** starts in the position of step_1 (one foot before the other) and weight of the body shifts to the front foot resulting in a forward motion of the upper body but not with the legs. **Sway_1** consists of a step_1 and a sway_0 in one continuous motion. **Sway_2** contains a sway_1 and followed by a backwards motion of the foot in front. Sway_2 also is one continuous motion without hesitation or pauses in the motion. Sway_2 and sway_0 do not end with a changed position of a foot compared to sway_1 cf. Figure 6.8 and Figure 6.9 for photos of a person swaying.

Figure 6.9: *This figure presents two pictures of a typical* `sway_0` *of a participant. In the left picture, the participant is shifting his body weight to the front foot and his back leg is bent slightly. In right picture the participant is shifting his weight onto the back foot and his toes of the front foot lift.*

Step-back

A *step-back* is equivalent to step. The only difference is that it is not a forward motion but a backward motion with respect to the moving body. There are also two motions **step-back_1** and **step-back_2** **Step-back_1** consists of only one leg or foot motion behind the other. **Step-back_2** includes also a motion with the other foot backwards in one fluent motion cf. Figure 6.10.

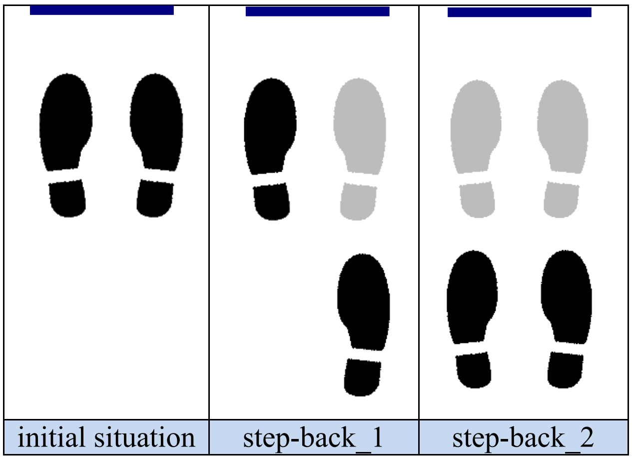

Figure 6.10: *The black footprints depict the actual place of the feet the participant after the motion ended. A grey footprint stands for a place which a foot had, before it ended at a position depicted by a black footprint. A blue bar marks the direction in which the robot (interaction partner) can be imagined cf. Figure 6.6 presents a picture of the robot and the participant. The step-back motions have a different initial position which is closer to the robot. All motions in this figure are away from the robot. In this figure* `step-back_1` *consists of the initial position and a motion of the right leg away from the robot.* `Step-back_2` *consists of a step-back_1 and an additional motion with the other leg backwards next to the foot which has been moved first.*

Sidestep

A *sidestep* is generally a motion to either side of and with the body. *Sidestep_1* is a leg and foot motion to the left or right side of this particular body. Consequently, a *sidestep_2* is a sidestep_1 and subsequently a motion towards foot which moved first. Figure 6.11 depicts these sidesteps as footprints.

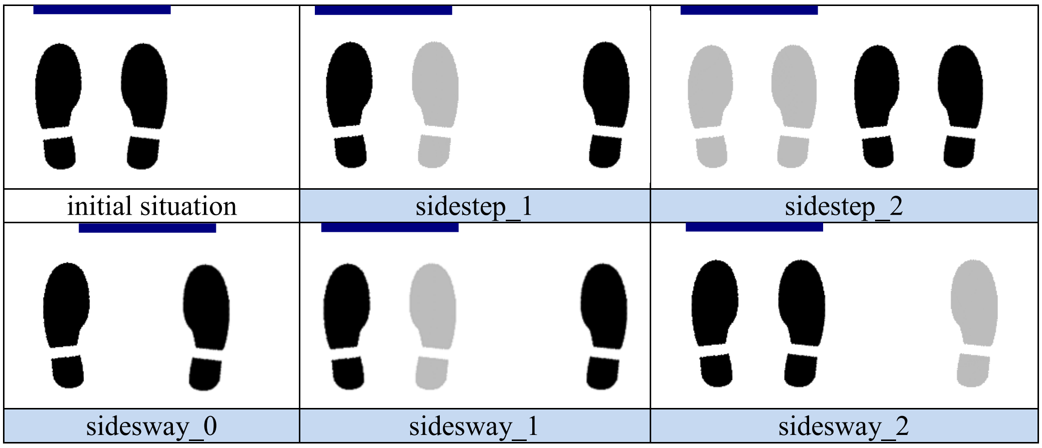

Figure 6.11: *The black footprints depict the actual place of the feet the participant after the motion ended. A grey footprint stands for a position which a foot had, before it ended at a position depicted by a black footprint. In each box, a blue bar marks the direction in which the robot (interaction partner) can be imagined cf. Figure 6.6 presents a picture of the robot and the participants. All motions depicted here, except sidesway_0 start in the initial position depicted in this figure. Sidestep_2 consists of a sidestep_1 and sidesway_2 consists of a sidesway_1. All sidesways have a shift of the body weight onto the leg which moved to the side. Sidesway_0 has shifts of body weight to either leg / foot or alternating body weight shift to both sides without a preceding leg motion.*

Sidesway

A *sidesway* is also a side motion like sidestep but additionally these motions have an extra weight shift of the body towards either side or back. This results in a motion in which the upper body is, relatively speaking, closer to something on the sides than the feet. A *sidesway_0* does not have an initial position as depicted in Figure 6.11 first drawing. A *sidesway_0* consists of only a sideward motion of the body with its weight so that the body is leaning to either side. A *sidesway_1* consists of a sidestep_1 and a sidesway_0. A *sidesway_1* is a continuously performed motion. That is why it is seen as one segment. A *sidesway_2* motion includes a sidesway_1 motion. Subsequently the moved leg is moved to the initial position, cf. the initial position in Figure 6.11 and Figure 6.12 for pictures of a person *sideswaying*. This motion is performed continuously.

Figure 6.12: *This figure presents two pictures of a typical* sidesway_0 *of a participant. The participant sways to the picture's right and shifts his body weight to the right foot in the left picture. In the right picture, the participant shifts his body weight to the left.*

Short Remark As defined in Section 2.6, new motioning intervals can start or end when there is a change in the direction of motion. However, the coding scheme for motionings does not agree with it completely in the case of body weight shifts (sidesway, sway). The reason for this is that the annotators of the motion intervals think that a sway (direction of body motion forward and backward) or a sidesway (direction of body motion to left and right) motion which was NOT interrupted by a pause or hesitation during the execution of the motion could NOT be divided. Furthermore, they rated this motion as one continuous motion even though there is a change in the direction of motion (back / forth, left / right). These motioning intervals are special compared to the statement of Van De Weghe et al. [2005]. Van De Weghe et al. [2005] state that humans perceive motion in a rectangular qualitative and relative way, namely, "left-right" motion and "toward-away" motion from their own perspective. A change of direction on either of those two dimensions results in a theoretical small pause in motion and in the annotation of a new motion. However, this theoretical small pause is not perceived by the annotators. This is the reason why sway_0. sway_2, sidesway_0, and sidesway_2 are annotated as a continuous motion and not as two motions. Even though, theoretically, there is a back and forth motion within the body weight shifts so that it ends at the position it has started.

6.3.2 Description of the Annotation of Motionings

Two coders annotated on the basis of the coding scheme for motionings the video data recorded with the camera mounted on Snoopy and with the external camera, which recorded the entire scene. For inter-coder reliability, and also the reliability of the coding scheme, Cohen's kappa was calculated [Cohen, 1968]. Cohen's kappa is a coefficient of agreement between two judges for nominal scales. The kappa value is 0.83. According to Pallant [2010], this means that there was a very good agreement between the coders.

51 whole-body motion intervals (or motionings) from 28 participants were identified within the leaving episode. 50% of participants only conveyed one motioning interval per leaving episode. The other 50% of participants conveyed 2-5 motioning intervals per leaving episode. That is why, the duration of the leaving episode is in average 20.4 sec. long (Md = 19.2 *sec.*, SD = 7.9 *sec.*) because it varies with number of motionings per participant.

With the description of the coding scheme for motionings the whole-body motions were categorised into the 12 categories cf. Section 6.3.1 and Figure 6.8 - 6.11.

For reasons of completeness, two hand gestures occurred during two motioning intervals, both signalling the robot to move away by moving the hand down and up at the wrist and showing the back of the hand. These are not further considered because they are not whole-body motions. *Step* motions occurred in 47.1% of the cases. The similar motion, *sway*, which includes step motions (sway_1 and sway_2), occurred five times. *Step-back* occurred seven times. *Sidestep* was annotated in 11 cases and *sidesway* in four cases, for detailed results see Table 6.1.

Motioning	Percentage
step_1	27.5%
step_2	19.6%
$\sum$ **step**	**47.1**%
sway_0	3.9%
sway_1	3.9%
sway_2	2%
$\sum$ **sway**	**9.8**%
step − back_1	11.8%
step − back_2	2%
$\sum$ **step-back**	**13.8**%
sidestep_1	11.8%
sidestep_2	9.8%
$\sum$ **sidestep**	**21.6**%
sidesway_0	2%
sidesway_1	3.9%
sidesway_2	2%
$\sum$ **sidesway**	**7.9**%

Table 6.1: *This table displays the count and categories of motionings found in the leaving episode. 51 motionings were found within the leaving episode of 28 participants.*

Collapsing Motioning Categories

For further analysis the 12 categories are firstly collapsed into five categories similarly to the description of *step, sway, step-back, sidestep, sidesway.* Then, the five categories are collapsed into three categories regarding similar performed motions in the direction of motion and distance relatively to the robot's position:

- Steps and sways are collapsed for reasons of similarity into the group ***step_ sway***. The motionings sway_1 and sway_2 both include the motioning step_1. All motions in this category are forward motions. Figure 6.8 depicts this category.
- ***Step-back*** stays alone as no similar motions in the backward direction were found in the leaving episode. Figure 6.10 depicts this category.
- The categories sidestep and sidesway are collapsed into one group ***side*** because the categories sidesway include categories of sidestep cf. Figure 6.11. The category side stands for motions to the left or right side of the participant in front of the robot.

The reason for collapsing the 12 categories into three motioning categories is that each category needs to have a certain amount of numbers to run a statistical test. In the following analyses, these three categories are considered (and their internal compositions are reported whenever the results seem interesting).

6.4 Analysing the Conditions and the Temporal Context of Motionings

A motioning is a temporal interval filled with communicative whole-body motion as explained in the coding scheme for motionings. These intervals have characteristics that describe them, delimit them from the group of motionings and from other intervals with different motions. The aim in this section is to describe and define motionings by their temporal characteristics and investigate as to whether they belong to the group of

- characteristics that describe the specific motioning categories, in other words, characteristics by which the motioning categories can be differentiated.

- characteristics that describe or separate the entire number of motionings from other motion intervals.

The characteristics, which are analysed in this section, are 'the frequency of motionings per participant', 'the duration of the motioning interval', and 'the duration of the interval of the succeeding pause', in short, the temporal context of motionings. To do so, some assumptions have to be tested first. First of all there are two conditions, this means, two groups of participants, who have either experienced a *less blocking* robot on the left side of the door frame of the printer room or more blocking robot in the middle of the door frame. The question here is whether the proportion of motioning categories in the less blocking condition is different from the proportion of motioning categories in the more blocking condition. As the proportion is not different (cf. Section 6.4.1), there are at least two tests to conduct for each characteristic to determine,

- whether these characteristics are differently distributed across the conditions and
- whether the characteristics describe the motionings specifically or generally.

6.4.1 Conditions and Motioning Categories

45% of the motionings occurred in the *less blocking* condition in which the robot was standing closer to the side of the door frame. 55% of motionings occurred in the *more blocking* condition in which the robot stood in the middle of the door frame.

A Fisher's exact test revealed that the proportion of motioning categories in the less blocking condition is not significantly different from the proportion of motioning categories in the more blocking condition (Fisher's exact test: $value = 1.485$, $p = .45$, $N = 51$)[5]. This result indicates that the motioning behaviour of humans towards robots in a passing by / blocking situation is the same regarding the conditions less and more blocking behaviour. This means it does not matter whether the robot is standing more or less in the way, giving the human about 20 - 55 cm more space in the door frame – the robot is blocking the path anyway. In other words, the motioning behaviour is robust for at least 20 cm of variation when the robot is blocking the path.

[5]The Fisher's exact test is a test for low sample frequencies and therefore preferred over χ^2 test cf. Appendix A and [Pallant, 2010]

Table 6.2 lists the characteristics with not significant results for the conditions. The outcome of the test can be read similarly to the one which is presented in this section. The table lists also the temporal characteristics which are presented in the following sections. Table 6.2 presents that the motioning categories do not have different proportions for each characteristic listed. This is why, the succeeding sections do not consider the conditions. However, in the following sections, each characteristic is checked for differences in the proportion of motioning categories to provide a detailed definition of motionings cf. Section 7.1.

Characteristic by conditions	**Statistical Test**
Motioning categories	Fisher's exact test: $value = 1.49$, $p = .45$, $N = 51$
Frequency of motionings per participant	Fisher's exact test: $value = 3.23$, $p = .61$, $N = 51$
Duration of motionings	Mann-Whitney U test: $z = -0.56$, $p = .58$, $N = 50$
Duration of succeeding pauses	Mann-Whitney U test: $z = -0.45$, $p = .65$, $N = 48$

Table 6.2: *This table lists the temporal characteristics of the motionings (from the third raw on) not having significant different proportions for the conditions less blocking and more blocking. Some tests were computed with a different total sample size (N). The reason is that outliners were identified which were outside the 1.5 times of the interquartile range (IQR). They were excluded to make sure that the statistical test would not only be not significant because of these outliers. The second raw provides an example how to read the outcome as it is explained in the main text. The result can be read in this way: the statistical test revealed that the proportion of [motioning categories] in the less blocking condition is not significantly different from the proportion of [motioning categories] in the more blocking condition. The temporal characteristics are explained in the following sections.*

6.4.2 The Frequency of Motionings per Participant

The frequency of motionings per participant in the leaving episode represents the number of motionings each participant conveyed during the leaving episode. 50% of the participants motioned once and the half motioned more than once (2-5 times). In this section, it is analysed, whether participants, who motioned only once, behave differently compared to the participants, who motioned more than once (considering the motioning categories). Furthermore, it is analysed, whether the motioning categories have different proportions across the first or second motioning per participant.

There is no difference in the proportion of motioning categories considering the first motioning of participants, who only motioned once and participants, who motioned more than once. This means that the 14 participants, who only motioned once, can be analysed together with the group of participants, who motioned more than once.

A Fisher's exact test revealed that there is a significant difference in the proportion of motioning categories for the first motioning compared to the second motioning per participant (Fisher's exact test: $value = 7.87$, $p = .02$, $c_{corr} = .66$, $N = 28$)[6]. The distribution of motioning categories for the first motioning and for the category *step_sway* is 64.3% (only consists here of steps) and for the category *side* 35.7% (only consists of sidesteps) cf. Figure 6.13 and Table 6.3. The distribution of motioning categories for the second motioning and for the categories *step_sway* and *step-back* are evenly distributed with 42.9% and only 14.2% for the category *side* cf. Figure 6.13 and Table 6.3.

This means that both, participants, who motioned only once and participants, who motioned more than once would take a step towards the robot or its side within their *first motioning* and *step-back* or *step_sway* for the *second motioning.* Transferring this behaviour to a robot in interaction with a blocking human: the different distribution of motioning categories for the first motioning suggests that a robot should use a motion similar to a human *step* as first motioning and a *step-back* motion as second motioning.

The characteristic *frequency of motionings per participant*, with its categories *first motioning* and *second motioning*, describes in which order motioning categories preferably occur. Therefore, this characteristic contributes to describe the specific motioning categories[7]

[6] The first motioning of participants, who motioned once and the second motioning of participants, who motioned more than once, were considered. That is why, the Fisher's exact test is used.

[7] This characteristic has to be included in the range of statistical tests to check whether there are dependencies to other characteristics as this characteristic describes the motioning categories specifically. As this is not the case and the statistical test will not be mentioned.

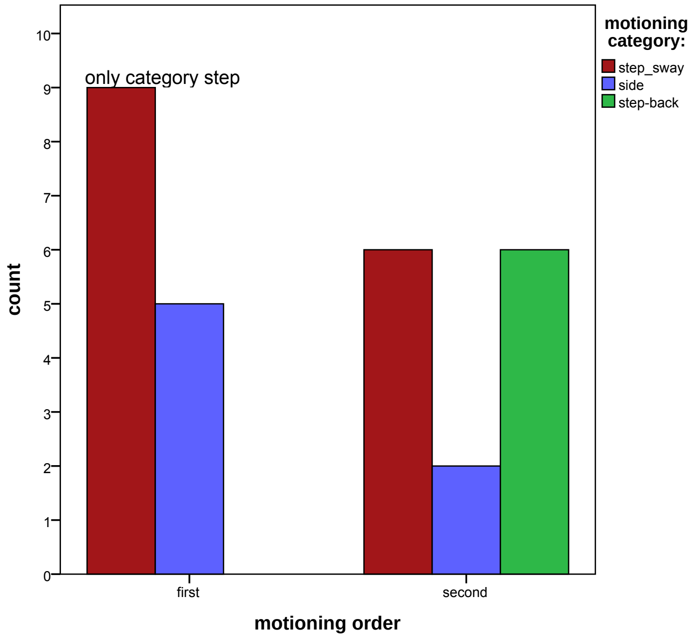

Figure 6.13: *The distribution of motioning categories is significantly ($p < .05$) different when comparing the* `first` *and the* `second` *motioning per participant in the leaving episode (Fisher's exact test: $= 7.87$, $p = .02$, $c_{corr} = .66$, $N = 28$). For this test, the first motioning of participants, who motioned once and the second motioning of participants, who motioned more than once, were considered. That is why, the Fisher's exact test is used. This is possible, because there is no difference in the distribution of motioning categories in the first motioning when comparing participants, who motioned only once, to participants, who motioned more than once.*

Characteristic	**Results**			
Frequency of motionings per participant	*Category* / *Frequency*	*step_ sway*	*side*	*step-back*
	first motioning	64.3%	35.7%	-
	second motioning	42.9%	14.2%	42.9%

Table 6.3: *This table displays the percentages of the proportion of the motioning categories (*`step_sway`*,* `side`*,* `step-back`*) for each category of the characteristics* `frequencies of motionings per participant` *(*`first motioning`*,* `second motioning`*).*

6.4.3 The Duration of Motionings

The duration of a motioning interval is a characteristic, which describes the entire number of motioning categories: a Kruskal-Wallis test revealed that the duration is not significantly different when comparing the duration of each motioning category to each other (Kruskal-Wallis test: $\chi^2(2,\ N = 50) = 2.05,\ p = .36)$[8]. Therefore, the duration of motionings is computed for all 51 motionings[9].

The duration of a motioning ranges between 0.61 sec. and 3.1 sec. ($M = 1.45$ *sec.*, $SD = 0.58$ *sec.*) cf. Table 6.4. One outlier was identified. The value was outside the 3 times of the interquartile range (IQR) and therefore is called an extreme outlier cf. [Pallant, 2010]). This outlier was longer due to some technical problem with the robot and was excluded from the analysis.

The time from the start of a motioning to the crossing of the doorsill ranges from 2.3 sec. - 20.7 sec. ($M = 7.5$ *sec.*, $SD = 5.2$ *sec.*). This means that a robot in such a situation has at least 2.3 sec. and on average 7.5 sec. to detect and react to a motioning.

The characteristic *duration of motionings* describes the entire number of categories of motionings within the leaving episode. This characteristic contributes to separate motionings from other kinds of whole-body motion.

Characteristic	**Results**		
	Range	Mean	SD
Duration of motionings	0.61 sec. - 3.1 sec.	1.45 sec.	0.58 sec.

Table 6.4: *This table displays the duration of motioning intervals.*

[8]The explanation of all statistical tests and notations can be found in the Appendix A in three tables (p. 211 f).

[9]A paragraph was excluded, which reports a minimal but significant difference in the duration of motionings in participants, who only motioned once ($M = 1.12$ *sec.*) and participant who motioned more than once ($M = 1.8$ *sec.*) when only comparing the participants from the more blocking condition cf. Appendix B.2.

6.4.4 Duration of Succeeding Pauses

Similar to the duration of motionings, the motioning categories do not have different durations of succeeding pauses (Kruskal-Wallis test: $\chi^2(2,\ N = 51) = 0.001$, $p = .99$).

It is defined in the preliminary definition of motionings (Section 2.6) that motionings can be separated through pause of motion or hesitation in the motion. That is why, it is not surprising that every motioning interval is followed be an interval of pause in motion. However, there are differences in the duration of these intervals.

Three extreme outliers were found and excluded from further pause analysis. Their value was outside the 3 times of the interquartile range (IQR) cf. [Pallant, 2010]. These outliers had extreme values due to technical problems with the robot at that time which might have caused the participant to stand still for a longer time.

A cluster analysis revealed two groups of pauses which differ in their duration. According to the Mann-Whitney U test the duration of pauses differ significantly for the two groups 'longer and short' pauses (Mann-Whitney U test: $z = -5.51$, $p = .001$, $r = .8$ (large effect), $N = 48$)[10].
Group 1 (long pauses) consists of 33 intervals of pauses with a duration of above 0.26 sec.: the duration is ranging from 0.3 sec. - 6.1 sec. ($M = 1.98\ sec.$, $SD = 1.9\ sec.$)[11]. Group 2 (short pauses) consists of 15 intervals of pauses that range only between 0.04 sec - 0.1 sec., ($M = 0.07\ sec.$, $SD = 0.02\ sec.$)[12] cf. Table 6.5.

The characteristic *succeeding pauses of motionings*, with its two groups of durations of intervals of pauses, describes the entire number of categories of motionings within the leaving episode. This characteristic contributes to separate motionings from other kinds of whole-body motion.

6.4.5 Short Summary of the Temporal Context of Motionings

The Tables 6.2 - 6.5 provide a quick overview of the conditions and of the temporal context of motionings: Generally, the *frequency of motionings* per participant de-

[10] The two groups of pauses are not differently distributed across the conditions more blocking and less blocking (Pearson $\chi^2(1, N = 48) = 1.15$, $p = .2$).

[11] There is also no difference in the duration of only those pauses (G1 long pauses) for the different motioning categories (Kruskal-Wallis test: $\chi^2(2,\ N = 33) = 0.5$, $p = .78$).

[12] The durations of these pauses (G2 short pauses) similar across the motioning categories (one-way ANOVA: $F(2,\ 15) = 0.521$, $p = .61$).

Characteristic	Results			
Duration of succeeding pauses	Groups \ Descriptives	Range	Mean	SD
	long pause	0.3 sec. - 6.1 sec.	1.98 sec.	1.9 sec.
	short pause	0.04 sec. - 0.1 sec.	0.07 sec.	0.02 sec.

Table 6.5: *This table displays duration of succeeding pauses of motionings divided into two groups with short pauses and longer pauses.*

scribes the specific motioning categories. The characteristics, *duration of motionings* and the *duration succeeding pauses* describe motionings in general and help differentiate motionings from other motion intervals. The motioning category *step_sway* occurred in 56.9% of the motionings and also occurs in 64.3% (only steps) of the first motionings. This motioning category could be a prototype of a motioning which occurs to spatially coordinate each other in a blocking situation robust to the conditions *more blocking* and *less blocking* . Transferring a the motioning category *step_sway* to a robotic way of motioning one needs to be careful about the fact that the robots such as Snoopy and BIRON are not able to sway with their entire body (Or should at least not sway for safety reasons). Fortunately, the motioning category *step* occurs in 47.1% of the motionings which is still a high number. Therefore there is no need to transfer swaying motions to such robots.

6.5 Analysing the Characteristics Position, Orientation, Distance and Trajectory

The characteristics *orientation of the person towards the robot, the position of the person relative to the robot, the distance between robot and person and the direction of motion (trajectory) of the person relatively to the robot*[13] were annotated semi-automatically in two steps for the motioning intervals. A student assistant rated these characteristics with the help of the synchronised videos (Snoopy's and external view) in ELAN[14] and with the help of the offline version of Human-Augmented-Mapping (HAM) cf. Figure 6.14 for an overview of the sources of information, for

[13]Short notation: relative position, relative orientation, relative direction, and relative distance.

[14]ELAN is a video annotation tool maintained by the Max-Planck-Institute for psycholinguistics cf. [Sloetjes and Wittenburg, 2008]: `http://tla.mpi.nl/tools/tla-tools/elan/` (last retrieved 20.08.2012)

HAM Section 6.1.3 and [Topp, 2008], and Figure 6.14 HAM displays a visualisation of the laser data with the robot position and human position on a mesh with 50 cm x 50 cm squares cf. Figure 6.14. These squares were again divided into again four equal squares of 25 cm x 25 cm and these were numbered to receive a detailed annotation. The exact distances between robot and human were calculated by the HAM system.

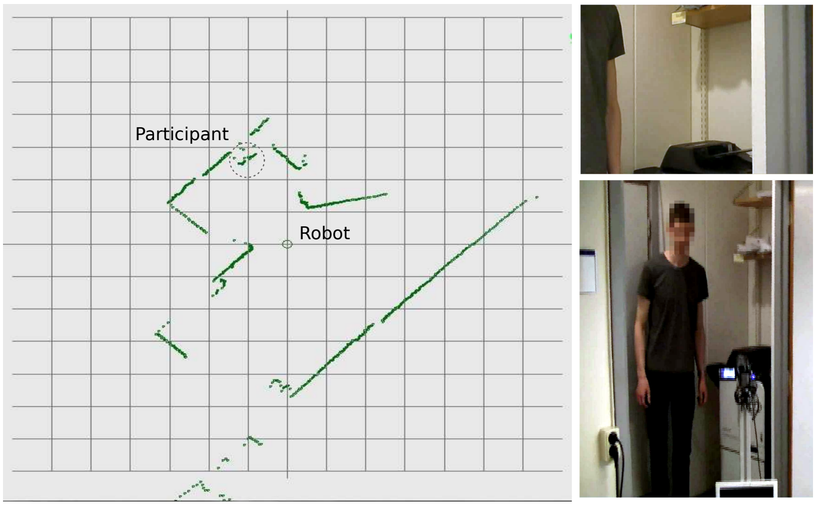

Figure 6.14: *This figure displays three times the same scene in the printer room recorded by: the robot data visualisation software HAM (left), the robot's video camera (top, right) and the external video camera (bottom, right). All three data sources were used to annotate the characteristics of motionings. The screenshot of HAM (left) displays a 50 cm x 50 cm mesh with the robot in the middle (circle in front of the printer room) and the participant with in the upper right corner of the printer room. The video data of Snoopy's camera and the external camera were annotated with ELAN (video annotation tool).*

The range of annotations was then collapsed into relative qualitative statements according to the idea of Qualitative Trajectory Calculus in [Van De Weghe et al., 2005; Van de Weghe et al., 2006]. Van De Weghe et al. [2005] states that humans understand relations between persons in a qualitative way, e.g., someone would say when describing another person's motion in relative relations like 'towards' and 'away' from me, or left and right of me instead of numbers in measurements like centimetres or degrees. Van De Weghe et al. [2005]; Van de Weghe et al. [2006] suggest to rate motion of a person in relation to another person with three categorical values. Inspired by Barrett et al. [2005] and Van de Weghe et al. [2006], four characteristics were chosen which the authors stated, were essential for representing motion and whole-body motion cf. Section 3.4. In general, the categorical and relative values for these characteristics were obtained regarding and answering the question whether the values indicate where the human in planning to go, e.g., therefore the value 'a human, who is oriented *towards* the robot' needs to be different to an 'orientation of the participant *past* the robot' because these little posture shifts can be interpreted in different ways, similar different interpersonal distances cf. Chapter 3. The characteristics *relative position, relative orientation, relative distance and relative trajectory* are presented in the following sections. Furthermore, each characteristic is classified into either a characteristic that describes the motioning categories or that describes the motionings in general in the same way the temporal characteristics of motionings are presented. Also, statistically significant differences in the proportion of these characteristics in regard to the conditions *less blocking* and *more blocking* are presented. The aim of these sections is to investigate also whether all four characteristics form patterns that describe a specific motioning category (*step_sway*, *side*, *step-back*).

6.5.1 Relative Position

The position of the participant in relation to the robot's position is represented by two categorical values: 'opposite' and 'diagonal'. The values were measured at the beginning of the motioning. Therefore, the characteristic relative position is not depending on the participant's motion, the characteristics relative distance and direction consider the change in motion. The positioning of people plays a role in identifying and categorising goal-directed motions cf. [Barrett et al., 2005] and Section 3.4.1. In addition interaction analysts found that different positioning between people have different meanings [Kendon, 1990].

The two values were created, because the person positioned herself / himself either 'diagonally' in front of the robot (diagonally to the right or left side of the robot' position but still in front) or directly 'opposite' in front of the robot. To decide which position is 'diagonal' and which position is 'opposite' the printer room was divided into 50 cm x 50 cm squares with the help of HAM. The square in which the robot had his position was the origin from which diagonal and opposite squares were measured: all squares, which were bordering on the side of the robot's square up to the wall of the printer room are annotated with 'diagonal' cf. Figure 6.15. The squares in front of the robot's position which are annotated with 'opposite', cf. Figure 6.15. Figure 6.15 sketches the printer room and the segmentation of the room into two positions with two different colours.

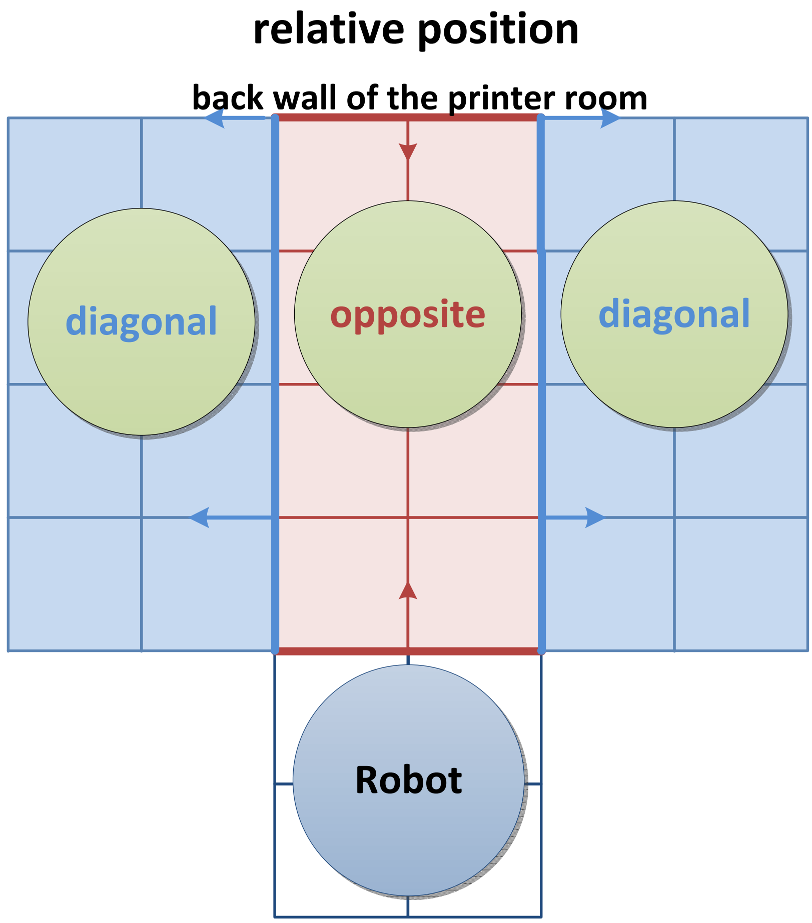

Figure 6.15: *This figure displays which* `relative position` *of the participant (green circles) are rated as 'diagonal' and 'opposite'. The position is always rated relatively. Each square stands for a 25 cm x 25 cm. Four of those squares are received by the offline version of the system HAM. HAM displays the participant's position and the robot's position. A student assistant rated the positions 'diagonal' and 'opposite' with this figure mind. This figure was modified depending on the position of the robot.*

Analysis of Relative Position

The first overview shows that 72.5% of the participants positioned themselves 'diagonally' to the robot and 27.5% 'opposite' of the robot cf. Table 6.6. A Pearson χ^2 test revealed that the proportion of the relative position values ('opposite', 'diagonal') are significantly different for the blocking conditions *less blocking* and *more blocking* (Pearson $\chi^2(1, N = 51) = 13.44$, $p < .001$, $c_{corr} = .49$).
None of the motionings were conveyed by the participants from the 'opposite' position when the robot was *blocking the door frame less* cf. Table 6.6. This means, whenever the robot provided more space, the participants would position themselves 'diagonally' to the robot - in the middle of the room. In contrast to the *more blocking* condition, here, participants were evenly distributed across the two positions. This means, a participant would either stand 'diagonally' to the robot or 'opposite' to the robot when the robot was *more blocking* cf. Table 6.6..

This result suggests that no participant would position oneself purposely in front of the robot (opposite) when it is *not* standing completely in the way. This behaviour might indicate the participants' wish to proceed to the next room, blocking the way themselves while standing in front of the robot would not be efficient.

This finding has no significant influence on the equal distribution of values 'diagonal' and 'opposite' across the different motioning categories[15]. However, there is a tendency that the motioning category *step_sway* occurs from a 'diagonal' position and the *side* motioning occurs from an 'opposite' position. Therefore, the characteristic *relative position* describes the initial situation at the beginning of a motioning in the leaving episode (a robot is blocking the path) in general. It has but also some differences across the motioning categories which will be considered when analysing patterns of characteristics cf. Section 6.5.3 and Section 6.5.7.

[15] The Fisher's exact test was only computed for the *more blocking* condition (Fisher's exact test: $value = 4.035$, $p = .12$).

Relative Position	occurrences	less blocking	more blocking
diagonal	72.5%	100%	50%
opposite	27.5%	–	50%

Table 6.6: *Overview of the characteristic* `relative position`*. The column 'occurrences' denotes the overall occurrences of the two values 'diagonal' and 'opposite'. The next two columns denote the percentages of the cross-tabulation of the characteristic relative position and the blocking conditions. The percentages are computed for each condition.*

6.5.2 Relative Orientation

Barrett et al. [2005] suggested to state the 'relative angle between one agent's orientation and the other's position (degrees)' when representing the whole-body motion of people cf. Section 3.4.1. However, for this thesis, values of characteristics are stated as categorical values regarding the idea of Van De Weghe et al. [2005]. In this case, the characteristic *orientation of the participants in relation to the robot's position* (short relative orientation) comprises two categorical values: the orientation 'towards' the robot and the orientation 'past' the robot as only those ones appeared. The relative orientation is defined by virtually setting an arrow on each shoulder, so that these arrows point orthogonally away from the front side cf. Figure 2.1 (p. 26) and Figure 6.16. The pointing direction is then compared to the position of the robot. A preliminary analysis found that the participants' body orientation points 'towards' the robot or towards the exit that is 'past' the robot. If a person would look straight ahead and has the head in line with her / his shoulders the arrows would point into the facing direction. Figure 6.16 displays the different relative orientation values a person had during the motioning intervals.

Analysis of Relative Orientation

The participants were directed towards the exit ('past') in two thirds of the motionings (66.67%) and in one third (33.33%), participants oriented themselves 'towards' the robot cf. Table 6.7. Similar to the characteristic relative position, the proportion of the values 'towards' and 'past' (relative orientation) are significantly different across the two conditions, *less blocking* and *more blocking* (Pearson $\chi^2(1, N = 51) = 6.187$, $p = .013$, $c_{corr} = .51$).
Also, similar are the patterns of proportions of the values 'towards' and 'past' across

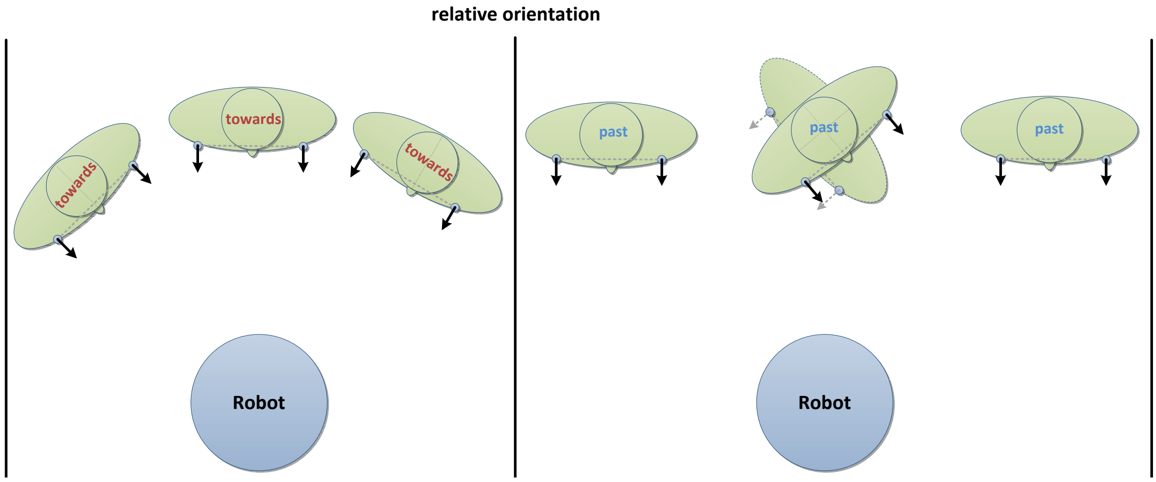

Figure 6.16: *The figure displays the different values of the characteristic* `relative orientation`*. The relative orientation is the body orientation of the participant compared to the position of the robot. To decide whether the body orientation is pointing 'towards' the robot or 'past' the robot (see the black arrows on the green sketches of the humans.*

the blocking conditions. In 87% of motionings, participants have the body orientation 'past' in the *less blocking* condition (13% 'towards') cf. Table 6.7. In the *more blocking* condition, both values occurred equally frequent cf. Table 6.7. In addition, there is also no significant difference in the distribution of the values of relative orientation across the different motioning categories (checked for each blocking condition separately and together)[16]. However, there is a tendency in both conditions that the relative orientation 'past' occurs whenever the motioning category *step_sway* was rated ('past': 81.5%, 'towards': 18.5%). In the *more blocking* condition, there is a tendency that the value 'towards' occurs more frequently when the motioning category *side* was annotated ('towards': 77.8%, 'past': 22.2%). This characteristic describes the situation (a robot is blocking the path) and the motionings in the leaving episode in general but also has some differences across the motioning categories which will be considered when analysing patterns of characteristics cf. Section 6.5.3 and Section 6.5.7.

[16]Motioning categories x relative orientation:
less blocking : Fisher's exact test: $value = 3.47$, $p = .16$,
more blocking : Fisher's exact test: $value = 5.25$, $p = .08$,
both conditions: Fisher's exact test: $value = 5.93$, $p = .06$.

Relative Orientation	occurrences	less blocking	more blocking
past	66.6%	87%	50%
towards	33.3%	13%	50%

Table 6.7: *Overview of the characteristic* `relative orientation`*. The column 'occurrences' denotes the overall occurrences of the two values 'past' and 'towards'. The next two columns denote the percentages of the cross-tabulation of the characteristic relative position and the blocking conditions. The percentages are computed for each condition.*

6.5.3 Combining Relative Position and Relative Orientation

The characteristics *relative position* and *relative orientation* were compared to each other to find possible patterns of co-occurrences of values. As both characteristics had different proportions across the conditions, the conditions have to be considered while testing. For the *more blocking* condition, a Pearson χ^2 test revealed a significant difference in the proportion of relative position and relative orientation (Pearson $\chi^2(1, N = 28) = 3.571$, $p = .023$, $c_{corr} = .56$). Participants, who position themselves 'opposite' the robot are oriented 'towards' the robot in 71.4% of the cases and only in 28.6% of the cases there were oriented 'past' the robot cf. Table 6.8. Participants, who positioned themselves 'diagonally' to the robot are oriented 'past' the robot in 71.4% of the cases (28.6% 'towards') cf. Table 6.8. This proportion of values is still significant for all the motionings without conditions (Pearson $\chi^2(1, N = 51) = 10.35$, $p = .001$, $c_{corr} = .63$). These patterns 'diagonal' & 'past' and 'opposite' & 'towards' are patterns which describe the initial situation of the beginning of the motionings in the leaving episode in general. The patterns are clearly recognisable when the robot is *more blocking* cf. Table 6.8.

pos. \ ori.	towards	past
opposite	71.4%	28.6%
diagonal	28.6%	71.4%

Table 6.8: *Percentages of the cross-tabulation of* `relative position` *(pos.) and* `relative orientation` *(ori.) with the cases from the* `more blocking` *condition only. The percentages are computed across the positions for each orientation.*

6.5.4 Relative Distance

The system for rating the relative distance QTC_{B1D} (Section 3.4.3) is transferred to describe the *change of distance between the participants and the robot* (short: relative distance). As the robot was stationary at the time of the motioning interval, the robot's part is not provided in the results. Consequently, there are only three categorical values of the characteristic *relative change in distance* to choose from: 'increase', 'decrease' and 'no change'. These values are similar to the values proposed by Van de Weghe et al. [2006]: 'increase' (+), 'decrease' (-) and 'no change' (0). The values are rated in relation to the position of the robot cf. Figure 6.17. Figure 6.17 illustrates the possible values of the characteristic *relative distance* (in short: relative distance). This characteristic is based on a semi-automatic approach to rate the distance in the motionings: a rater assigned the values ('increase', 'decrease' and 'no change') to the motioning intervals with the help of the video data and the HAM system. Unfortunately, the exact distances which were produced from the laser readings were erroneous in 20% of the cases and had to be controlled by the rater.

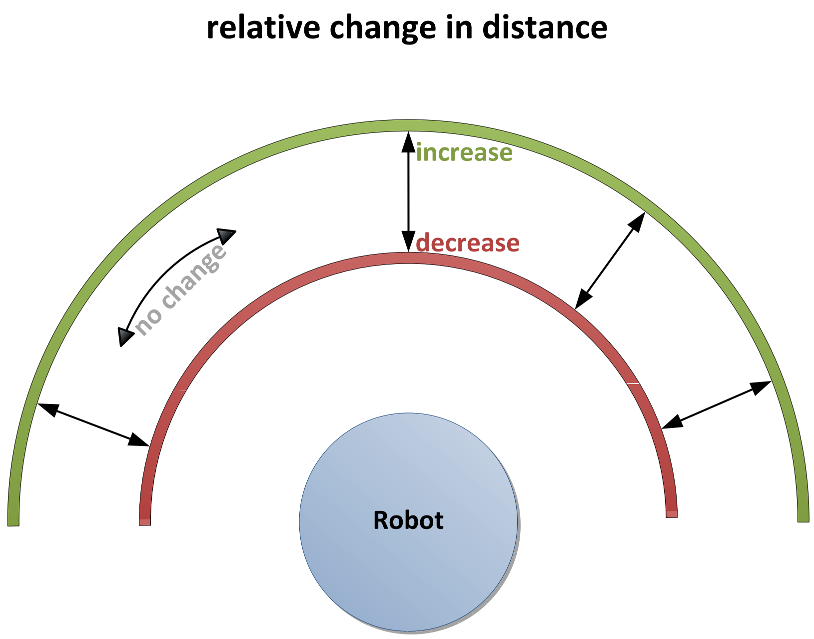

Figure 6.17: *This figure illustrates the features of the* `relative change in distance` *considering the persons motions. The features 'no change', 'increase' and 'decrease' in distance are rated for each motioning interval in the leaving episode. Human motion is illustrate through the arrows. The robot is depicted as a blue circle.*

Analysis of Relative Distance

The mean values of the distances at the beginning of the motionings are stated, here, to provide an overview of the exact interpersonal distance from the robot for each of the values: 'decrease', 'no change', and 'increase'. Generally, participants stood on average 42 cm away from the robot ($SD = 14.7\ cm$) cf. Table 6.9. The mean distances at the beginning of the motionings are significantly different when comparing the values 'decrease' ($M = 45.2\ cm$, $SD = 10.8\ cm$), 'increase' ($M = 35\ cm$, $SD = 12.3\ cm$), and 'no change (nc)' ($M = 43\ cm$, $SD = 19.1\ cm$) to each other[17]. The mean distances in cm correspond to the intimate zone Hall [1966] proposed cf. Section 3.5. This information can be used to differentiate motionings from other motions (cf. Section 6.6).

Furthermore, in 45.1% of the motionings, participants 'decreased' their distance during the motioning intervals with an average of 11.1 cm ($SD = 4.9\ cm$) cf. Table 6.9. This is a statistically significant 'decrease' of the distance from the beginning of a motioning ($M = 45.2\ cm$, $SD = 10.8\ cm$) to the end of a motioning ($M = 34.4\ cm$, $SD = 11\ cm$) (paired samples t-test: $t(22) = 10.595$, $p < .001$, $\eta^2 = .84$ (large effect)) cf. Table 6.9. 29.4% of the participants did 'not change' (nc) their distance to the robot ($M = 43\ cm$, $SD = 19.9\ cm$). Furthermore, 25.5% of the participants significantly 'increased' the distance between them and the robot with an average of 8.08 cm ($SD = 3.3\ cm$) at the beginning of the motioning ($M = 35\ cm$, $SD = 12.3\ cm$) compared to the end of a motioning ($M = 43.9\ cm$, $SD = 13.1\ cm$) (paired samples t-test: $t(12) = -5.842$, $p < .001$, $\eta^2 = .74$ (large effect)) cf. Table 6.9.

Relative Distance	occurrences	all		Beg. of M.I.		change	
		M	SD	M	SD	M	SD
decrease	45.1%	42cm	14.7cm	45.2cm	10.8cm	11.1cm	4.86cm
no change	29.4%			43cm	19.1cm	—	—
increase	25.5%			35cm	12.3cm	8cm	3.3cm

Table 6.9: *Overview of the* `interpersonal distances` *between the participant and the robot.* `Occurrences:` *overall occurrences of the values of relative distance.* `Beg. of M.I.:` *Beginning of the motioning interval.*

[17] Three t-tests were conducted:
increase & decrease: $t(34) = -12,4$, $p < .001$
decrease & no change (nc): $t(22) = -10.6$ $p < .001$
increase & nc: $t(12) = 8.95$, $p < .001$.

The interesting question for the characteristic relative distance is: Is the proportion of the categorical values of the relative distance different across the motioning categories? A Fisher's exact test revealed that the proportion of the categorical values of distance ('increase', 'decrease', 'no change') is different for each categorical motioning category (*step_ sway*, *side*, *step-back*) (Fisher's exact test: $value = 27.25$, $p < .001$, $c_{corr} = .77$).

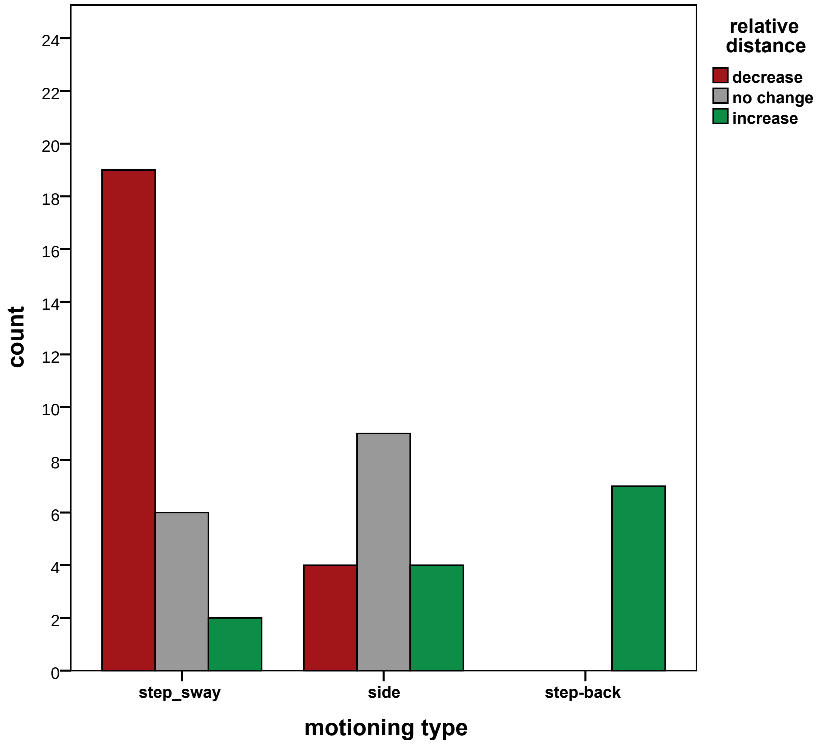

Figure 6.18: *This figure displays the different proportions of the values of the characteristics* `relative distance` *for each motioning category. There is a tendency that each value only occurs for different motioning category the most. The absolute count of motioning is displayed to get an overview of the full information. Normalising across the values or motioning categories would take information away. See text and Table 6.10 for percentages for cross-tabulation of motioning categories and the values of the relative distance.*

Figure 6.18, displays the different proportions of the values of the characteristic *relative distance* for each motioning category. Figure 6.18 presents also that for each motioning category a different value occurs the most. The value 'decrease' occurs within the motioning category *step_ sway* in 70.3%[18] cf. Table 6.10. The value 'no change' occurs in 52.9% when the motioning *side* was annotated cf. Table 6.10. The motioning category *step-back* is solely explained by the 'increase' of distance but the

[18]Normalised across the values for each motioning category.

value ’increase’ of distance occurs with other motioning categories cf. Table 6.10 and Figure 6.18.

The general conclusion is that the characteristic ’relative distance’ alone cannot differentiate exactly the three different motioning categories but has a tendency to do so, e.g. an occurred value ’increase’ can help to decide whether an motioning category is a *step-back* or some other category. Section 6.5.6 and Section 6.5.7 provide for further analyses of the predictive ability of the characteristic for the motioning categories.

distance / motioning category	**decrease**	**no change**	**increase**
step_sway	70.4%	22.2%	7.4%
side	23.5%	52.9%	23.5%
step-back	–	–	100%

Table 6.10: *The percentages of the cross-tabulation of* `relative distance` *and the* `motioning categories`*. Percentages are computed across the values of relative distance for each motioning category.*

6.5.5 Relative Trajectory

The qualitative values for the characteristic *relative change in the direction of motion* (in short: relative trajectory) are obtained in a similar way than they are obtained for the characteristic relative distance. Furthermore, Van De Weghe et al. [2005] suggest to represent motion of entities by describing their trajectories with respect to each other in the same way than describing the motion via distance cf. Section 3.4.3). Van De Weghe et al. [2005] suggest to rate this in two dimensions: left-right and towards-away. Each of these dimensions has three values, either: ’towards’, ’away from’, ’no change in motion’ or ’left’, ’right’, and ’no change in motion (or moving along the other dimension)’ cf. Section 3.4.3). Consequently, 81 combinations of a 4-elements state descriptor (QTC_C relation) describe the trajectories of two entities (Section 3.4.3).

However, not all 81 combinations of trajectories are used for rating the trajectories of the participant’s motion within the motioning intervals. The *relative trajectory* is defined as the direction of the participant’s whole-body motion within the motioning interval compared to the position of the robot. 8 combinations of the 81 are needed, the others were ruled out because the robot did not move during the motionings cf.

Figure 6.19. The 8 combinations were collapsed into three nominal categories because the information which is interesting and needed is whether the trajectories indicate that the person and the robot would collide. Obtaining this information is motivated by the fact that humans in the position of the robot would feel the urge to increase the distance cf. Section 3.5 - 3.6. Additionally, the information, which is needed from the QTC_C is whether the person is moving *towards* or *away* from the robot but also whether a person is passing by or whether the trajectories of the participant point 'past' the robot Therefore, the 8 combinations can be collapsed. To obtain a low number of categorical categories, the 8 QTC_C relations were newly annotated: the combinations for 'past' were not collapsed with relations standing for a 'towards' motion. Furthermore, left and right of the left-right dimensions were newly annotated with 'towards' and 'away' from the robot.

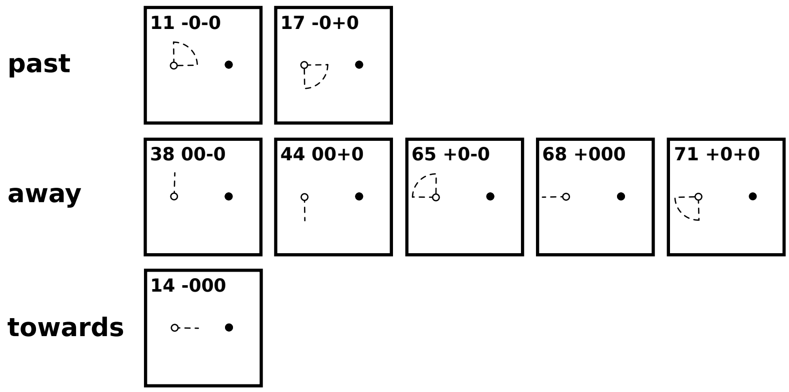

Figure 6.19: *The figure displays the 8 relations or 4-element state descriptors which Van De Weghe et al. [2005, p.64] defined (Section 3.4.3). The '0' values stand for the robot, which is not moving at all (filled black dots). The '+' and '-' values stand for the participant's motion as depicted left of the filled black dot. The 8 relations were collapsed into three new categorical values: 'past', 'towards' and 'away' as labelled in this figure. Figure 6.20 displays the trajectories in global sketch.*

Figure 6.19 presents the 8 relations and their new annotations. The information, whether
a) the participant is moving *away* from the robot but is staying inside the room (newly annotated with 'away')
b) the participant is directly moving *towards* the robot (on collision path)(newly annotated with 'towards')
c) the participant is moving towards the door but *past* the robot (newly annotated with 'past')
are especially interesting for motionings in a passing by scenario to infer whether the participant is signalling through her / his trajectories what the she / he wants cf. Figure 6.20. Note that the values 'towards', 'away' and 'past' represent the trajectories of motion for motioning. That does not mean that the participants actually moved out of the room within a motioning but their trajectories pointed in that direction. The value 'towards' includes also motions into the focus of the robot towards the 'opposite' position of the robot (cf. towards_focus in Figure 6.20. The annotation 'towards_focus' is a tricky case because they are also represented by the relation 11 or 17 cf. Figure 6.19 which stand also for 'past'. For these values, the environment was taken into the account to decide whether or not these trajectories should be assigned to 'towards' or 'past'. Therefore, the values of the characteristic *relative trajectory* do not necessarily correspond to the values of the characteristic *relative distance* ('increase', 'decrease', 'no change'). Moreover, motionings like *sway* and *sidesway* have trajectories but do not necessarily have a change in distance. Naturally, a 'decrease' in distance occurs together with trajectories 'past' or 'towards' but as stated before 'past' and 'towards' occur also with the value 'no change' (distance). Figure 6.20 displays the possible values for trajectories of participants in relation to the robot in the sketched printer room environment.

Analysis of Relative Trajectory

43.1% of the *relative trajectories* of the motions within the motionings pointed 'towards' the robot. 35.3% of the *relative trajectories* pointed 'past' the robot and 21.6% of the trajectories pointed 'away' from the robot somewhere to the wall the printer room cf. Table 6.11.

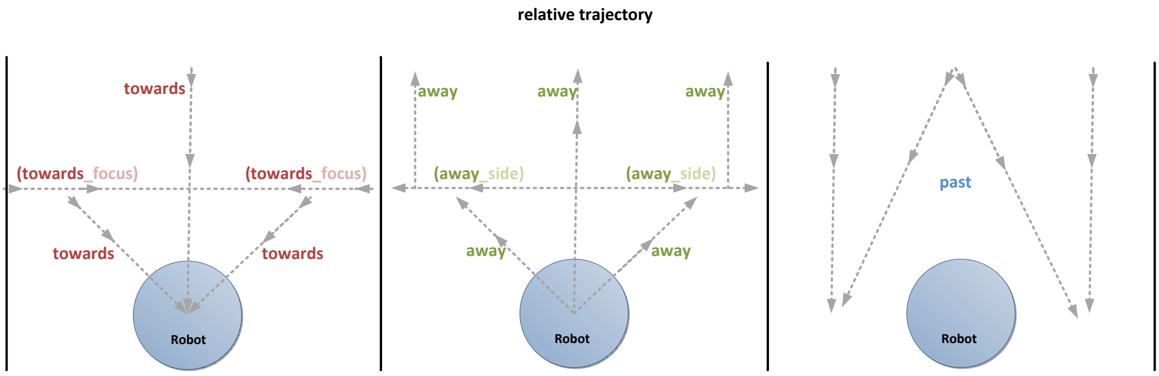

Figure 6.20: *This figure displays the values for the characteristic* `relative trajectory`*: 'towards' the robot, 'away' from the robot and 'past' the robot. To obtain the value, the trajectories which are pointing in the direction of the participants' motions within the motioning are compared to the robots position. The arrows display the direction of motion of the participants in relation to the robots position (circle). In addition this figure sketches the motion of the participant in the printer room, which makes the view more global than Weghe et al.'s sketches cf. Figure6.19. This is done for a better understanding of the occurred trajectories.*

rel. trajectory	**occurrences**
towards	43.1.4%
past	35.3%
away	21.6%

Table 6.11: *Overview of the occurrences of the values of* `relative trajectory`

Similar to the characteristic distance, the proportion of the categorical values of relative trajectory ('towards', 'past', 'away') is different for each categorical motioning category (*step_sway*, *side*, *step-back*) (Fisher's exact test: $value = 31.07$, $p < .001$, $c_{corr} = .79$). Figure 6.21 displays the proportion of relative trajectories for the motioning categories. In each motioning category is a different value of the characteristic relative trajectory more frequent compared to the other values: within *step_sway*, 55.6% of the values are 'past' ('towards': 44.4%, 'away':0%), whereas the value 'towards' occurs more frequently (58.9%) within the motioning category *side* compared to the other values of relative trajectory ('past': 17.6%, 'away': 23.5%). The motioning category *step-back* is solely represented by the value 'away'. Similar to relative distance, this characteristic describes the specific motioning categories.

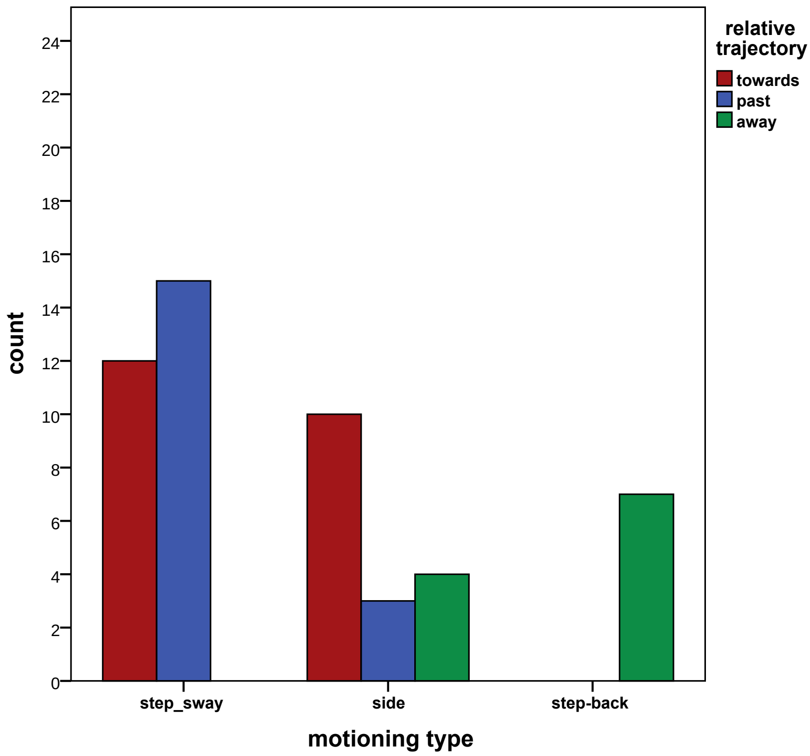

Figure 6.21: *The proportion of the values of* `relative trajectory` *('towards', 'past', 'away') and motioning categories (*`step_sway`*,* `side`*,* `step-back`*) is displayed. The proportions of the values are significantly different for each of the motioning categories. Table 6.12 presents the percentage for the cross-tabulation 'motioning category' x 'relative trajectory'.*

category \ trajectory	**towards**	**past**	**away**
step_sway	44.4%	55.6%	–
side	58.9%	17.6%	23.5%
step-back	–	–	100%

Table 6.12: *The percentages of the cross-tabulation of* `relative trajectory` *and* `motioning categories`*. Percentages are computed across the values of relative trajectory for each motioning category.*

6.5.6 Multinomial Logistic Regression: Relative Trajectory and Relative Distance

The outcome of the analyses of the characteristics *relative distance* and *relative trajectory* is that both characteristics have significantly different proportions of values for each motioning category. Thus, these characteristics can be taken to predict the motioning categories. The multinomial logistic regression (MLR) is used to determine the predictive power of the characteristics cf. [Pallant, 2010] and [Backhaus et al., 2011]. The MLR is a technique to determine the impact of a set of predictors (independent variables: relative distance and relative trajectory) on a dependent variable (motioning category). In contrast to the regression analysis for continuous data the MLR is used when the dependent variable is categorical and the independent variables have more than two categories (values) per variable and their data is nominal. However, both analyses try to compute weights for independent variables which influence the probability of occurrence for a distinct case of the dependent variable (*step_sway*, *side*, *step-back*) cf. [Backhaus et al., 2011]. The MLR tests also how well a set of independent variables fits to explain the dependent variable [Pallant, 2010]. In other words the MLR tests whether there is a pattern in the combinations of the independent variables (relative distance, relative trajectory) which occurs frequently and fits to explain the categories of the dependent variable (*step_sway*, *side*, *step-back*).

MLR Analysis

There are assumptions which have to be tested before using the MLR cf. [Pallant, 2010]. The pretests have been conducted according to [Pallant, 2010] and Backhaus et al. [2011]. There is no multicollinearity between the characteristics relative trajectory and relative distance. Likelihood ratio test tests whether there is any possibility that the characteristics have a predictive ability. This means whether the hypothesis 'H_0= All regression parameters are zero', can be rejected. The $\chi^2(8, N = 51) = 51.17$ reveals that this is the case ($p < .001$). This is a first support that the model fits (the characteristics have any predictive power). According to the pseudo-R Square statistics of Cox & Snell R Square and Nagelkerke R Square, 63.3% to 73.8% of the variability of the dependent variable is explained by the model. Each characteristic significantly fits the model (relative trajectory: $\chi^2(4,\ N = 51) = 18.7$, $p < .001$ and relative distance: $\chi^2(4,\ N = 51) = 12.63$, $p = .013$. The model correctly classified 78.4% of the cases overall. It is a small sample size, therefore the predicted value for each pattern is not stated. Instead the actual observed frequencies in per cent are stated cf. Table 6.13.

The multinomial logistic regression states that *step-back* can be described with the values 'away' (trajectory=(t)) together with 'increase' (distance=(d)). This pattern ('away'(t) & 'increase' (d)) occurs in 87.5% of the cases with the motioning category *step-back* and in 12.5% when the motioning category *side* was annotated cf. Table 6.13. The differentiation between the motioning categories *side* and *step_sway* is not as clear as the distinction compared to *step-back* cf. Table 6.13. There are three additional patterns, which illustrate that 'decrease' (distance) occurs frequently with *step_sway* but is indifferent to the co-occurring trajectories 'past' and 'towards' cf. Table 6.13. Generally, the trajectory 'past' occurs more frequently with the motioning category *step_sway* (85.6%). The motioning category *side* occurs with 'no change' in distance and a trajectory 'towards' in 55.5% of the occurrences of this pattern compared to the other motioning categories. This tendency is also visible in Figure 6.18 and Figure 6.21.

The MLR provides support for the interpretations of the results of the cross-tabulation of motioning categories and the characteristics relative distance and relative trajectory cf. Section 6.5.4 and Section 6.5.5 and Table 6.13. However, the limitation of the MLR is that the total sample size is only 51, which is a small number and results in low frequencies of occurrences in each cell. Therefore, further analyses of the MLR are not presented.

P	characteristic		motioning category		
	distance	**trajectory**	**step_sway**	**side**	**step-back**
1	increase	away	–	12.5%	87.5%
2	decrease	past	85.6%	14.3%	–
3	decrease	towards	77.8%	22.2%	–
4	no change	towards	45.5%	55.5%	–

Table 6.13: *This table displays the percentages of the multinomial logistic regression (MLR) of the characteristics* `relative distance` *and* `relative trajectory` *for the motioning categories. The percentages of the MLR are the observed frequencies for each pattern across the motioning categories. The overall classification rate was* 78.4% *with the knowledge of these characteristics. It is a small sample size, therefore the predicted value for each pattern is not stated. The MLR computed four patterns (P) that predict the specific motioning categories. When P 1 occurs it is more likely that it was annotated with a* `step-back` *(*87.5%*). When P 2 and P 3 occur it is more likely that they are motionings from the motioning category* `step_sway` *(*85.6% *and* 77.8%*). The motioning category* `side` *is not as clearly differentiated from* `step_sway` *compared to the motioning category step-back.*

6.5.7 MLR of all four Characteristics

As a summary of the analyses of the four characteristics, a MLR is conducted to investigate whether there are any patterns of the characteristics that describe specific motioning categories in combination with the characteristics that describe the situation of the beginning of a motioning interval. The pretests are similar to the pretests of assumption presented in Section 6.5.6. The four characteristics (the model) are a better than chance to predict the motioning categories. The exception, of course, is that the characteristics relative orientation and relative position are not significantly different distributed across the motioning categories. Therefore this analysis is a process to summarise the analysed characteristics and compute tendencies of the predictive power. Furthermore, there are only 51 motionings, which is a small sample size for MLR with four characteristics. Therefore the results are highly tentative but provide a good overview.

There are 36 possible combinations of values of the characteristics relative trajectory (3 values), relative distance (3 values) and relative orientation (2 values) and relative position (2 values)[19]. Only 18 combinations occurred. If all 51 motionings were evenly distributed across these 18 combinations, each combination would have a count of

[19] 36 combinations of values: $3 \times 3 \times 2 \times 2 = 36$

2.8 motionings[20]. This number was set as a threshold for combinations or patterns to be noted / analysed. *Four* of those 18 combinations had a count of more than 3 motionings. There is especially one pattern that should be emphasised because 21.6% of the motionings occurred in this pattern and only came from the motioning category *step_sway* cf. Pattern 1 in Table 6.14. Three additional patterns (combinations) were also above a count of 3 motionings cf. Pattern 2-4 in Table 6.14. Table 6.14 presents the four patterns with percentages of occurrences of the pattern compared to the occurrences in the other motioning categories[21].

P	characteristic				motioning category		
	position	**orientation**	**distance**	**trajectory**	**step_ sway**	**side**	**step- back**
1	diagonal	past	decrease	past	100%	–	–
2	opposite	towards	decrease	towards	100%	–	–
3	opposite	towards	no change	towards	25%	75%	–
4	all	all	increase	away	–	14%	86%

Table 6.14: *Multinomial logistic regression of all four characteristics (relative position, relative orientation, relative distance, relative trajectory). Four patterns have a higher frequency of motionings than it would have been the case when all motionings were evenly distributed across the 18 combinations that occurred.*

6.5.8 Summary

The analyses of the characteristics show that the relative orientation and the relative position of the participant at the beginning of the motioning intervals are influenced by the conditions *less blocking* and *more blocking* but do not have a different proportion for the motioning categories cf. Section 6.5.1 and cf. Section 6.5.2. There are basically two patterns of combinations of the values of the characteristics which occur more frequently than the other two: 'diagonal' & 'past' and 'opposite' & 'towards' (position & orientation) cf. Section 6.5.3.

The other two characteristics, relative distance and relative trajectory, describe the actual motion of the participants during the motioning interval. These values are not differently distributed for the conditions, but are differently distributed across the

[20] The threshold for an even distribution considering all 36 possible combinations is very low wit 1.4 motionings per combination so it was set higher.

[21] The patterns can be also found in the condition *more blocking* . The condition *less blocking* has only motionings which started from the diagonal position.

motioning categories cf. Section 6.5.4 and cf. Section 6.5.5. The results state that there is a tendency that a different value of those characteristics represent a different motioning category cf. Section 6.5.4 and cf. Section 6.5.5. Thus there are patterns of values which describe the specific motioning categories: *step_sway*: decrease & past, *side*: no change & past, and *step-back*: increase & away cf. Section 6.5.6. The 30 cm of additional space which distinguish the blocking conditions does not seem to make such a large difference on these characteristics – the behaviour (motion) in the motioning does not change. In other words, these characteristics are robust to small changes in the blocking behaviour of Snoopy. The robustness of these characteristics is an advantage when trying to find patterns of values which describe the specific motioning categories from humans towards robots. The combinations of all characteristics is presented in the latest Section 6.5.7 therefore it is not represented here. This analysis was an analysis to test whether the created coding scheme for motionings which was based on natural descriptions of motions has characteristics that describe and differentiate the coding scheme. This was done to verify the coding scheme and bridge the gap between human descriptions of motion and describing characteristics, which can be also represented by a robotic system. The analyses show that the positioning and orientation depends on the situation (condition) but the motion as such does not. The values of relative trajectory and the values of relative distance can be used to transfer different motionings to a robotic system. The limitation is that these characteristics might not be the only ones to represent a motioning for a specific situation. The relative position and the relative orientation describe the initial starting point of a motioning in the leaving episode. With the duration of motioning, the duration of the interval of pauses in motion and the absolute interpersonal distances motionings can be identified. The next section presents a short qualitative analysis of motion intervals from different episodes with the regard of the newly found information of the analyses.

6.6 Comparison of Motionings to Other Motion Intervals

The motioning categories which were found in the leaving episodes are compared with other motion intervals of other episodes of the same study.

Of course, it is expected that human whole-body motion intervals occur in different episodes, the first question is whether they can be found with the coding scheme for motionings plus the descriptions of the characteristics (duration, pause, position, orientation, distance, trajectories). The second more pressing question is whether these motion intervals which are very similar to the profiled ones, could also be motionings about something else and therefore meaningful hints of how to express a certain intention. Newly found motioning intervals of other episodes could also shed light on the question how to generalise motionings and what to add to the coding scheme.

The leaving episode is a time interval between a presenting (room and items) and a guiding (to another room) episode cf. Figure 6.3 (p.118). The *guiding episode* and the *presenting episode* will be in the focus of this investigation.

A *guiding episode* is defined as the time interval in which the participant guided the robot from one room to another usually within that episode the participant commanded the robot to follow. The episode starts when the participant crosses the doorsill out of the room and ends when the participant starts the next episode, here, it is always a presenting episode.

A *presenting episode* is defined as the time interval in which the participant presented the items and the room to the robot. The start and the end of this presenting episode are conforming to the 'show phase' in [Hüttenrauch et al., 2006b; Topp, 2011]. This episode starts with the first kind of presenting gesture or speech and ends with the start of a pause in motion after the last item has been presented, which is here the start of the leaving episode (at least in the printer room). Three kinds of presenting gestures (for the location, the regions, the objects) are taken as an indication for a start of the presenting episode [Topp, 2011].

Generally, the episode start is the end of the preceding interval and vice versa. This was done to include all possible motion intervals in one of the episodes.

6.6.1 Analysis of the Episodes

Each participant, who was analysed in the leaving episode, was considered. All of the guiding episodes and all presenting episodes of each participant are considered in the analysis.

The human whole-body motion intervals that correspond to motions of the coding scheme (Section 6.3.1, p.126) and are within the range of the duration of motionings 0.61 *sec.* − 3.1 *sec.* (Table 6.4, p.139) and have surrounding pauses which correspond to the duration of the intervals of pauses 0.04 *sec.* − 6.1 *sec.* (Table 6.5, p.141).

There are 74 *presenting episodes* with 110 motion intervals. 51% of the motion intervals are within the time range. These are on average 1.28 sec. long ($SD = 0.56$ *sec.*). The time intervals matched also a motioning category described by the coding scheme for motionings.

There are also 74 *guiding episodes* with 325 motion intervals. 8% of the time intervals are within the range duration of motioning intervals and are on average 1.45 sec. long ($SD = 0.48$ *sec.*). These intervals could be compared with one of the motionings from the coding scheme.

Theoretically, these time intervals are 'false positives' because the coding scheme was created on the basis of the leaving episode but matching motion intervals were also found in other episodes. Considering the questions stated in the beginning of the section, the question, here, is whether these false positives are really false positives or whether they are motionings for other situations. To find differences and similarities the false positives are qualitatively investigated with regard to the situation dependent characteristics (relative position and orientation) and with regard to the motioning dependent characteristics, relative trajectory and relative distance.

Motion Intervals of the Presenting Episodes

The 51% of the motion intervals are compared with the motionings of the leaving episode divided into three paragraphs: similarities to and differences from the motionings and a discussion whether or not the motion intervals are false positives.

Similarities: The motioning categories *step, sidesway, sidestep,* and *step-back* occur. The relative positions of the participants are very similar: 'opposite' and 'diagonal'.

Differences: *Side* motionings occur the most (*side* : 75%, *step*: 18%, *step-back* : 7%). All intervals occurred together with arm and hand motions either grasping an object, holding it, touching it or putting an object away. The participants needed to move in order to grasp the object, touch it, and put the object away. The average distance between participants and robot is 107 cm ($SD = 22.3\ cm$). This is about 65 cm further away from the robot compared to the average distance in motionings in the leaving episode cf. Table 6.9 (p.150). Also the change of the relative distance is bigger. The range for 'increasing' the distance is 15-40 cm and for 'decreasing' distance 15-30 cm (compared to $M = 8\ cm$ and $M = 11\ cm$) cf. Table 6.9 (p.150). Only relative trajectories 'away' from and 'towards' the robot are recorded. The participants' motions are not directed 'past' the robot. There are also differences in the characteristic orientation. The orientation describes the state of the beginning of a motioning interval. In 50% of the cases L-shape orientations occurred [Kendon, 1990]. L-shape formation means that the shoulders of two persons form an L when a virtual line between the shoulders of each person is drawn [22]. According to the coding of characteristic orientation, this L-shape formation can be expressed as the relative orientation 'away', which did not occur for the motionings in the leaving episode.

Discussion of False Positives The motion intervals which are coupled with grasping an object, touching it and putting are motions serving the purpose of manipulating the object. Naturally, these motions communicate either and do so in an indirect way. These short and abrupt whole-body motions might also evoke attention [Moon et al., 2011]. These interpretations are conforming to the preliminary definition of motionings in Section 2.6 (p.30).

However, the overall goal of the participants in the presenting episode was to present items to the robot. The conveyed whole-body motions are not the primary source of movement. Hand and arms moved more often. Considering the overall goal, the whole-body motions were not conveyed to spatially coordinate with the robot. They were conveyed in order to show objects. This means that the robot is not motioned to

[22] Both lines together form the letter L

make room because the goal of the manipulation was the object's position and not the position of the robot. These motions correspond to the main parts of the definition motionings but are different in the overall goal of spatial coordination and manipulation of the position of the interaction partner. Therefore an update of the definition of motionings is to clearly differentiate between overall goals such as spatial coordination vs. presenting and group similar situations according to their overall goal. In general the question remains whether or not to equip the coding scheme with a broader field of values of characteristics or to limit the definition to one group of situations and to limit the definition solely to occurring whole-body motions without any other motion of the body. For this thesis, however, the definition is further narrowed to motionings for spatial coordination reasons only and to solely occurring whole-body motion without any other source of primary motion. Primary motion means that there should be no other source of movement with a higher intensity of motion than whole-body motions, e.g., single noise scratching or eyelid movements would be disregarded. This is done to have a specific definition for motionings in spatial coordination situations. Another idea, how to decide whether or not a motion interval is a motioning, is by regarding the characteristics more strictly. As mentioned before the change of distances and the average distance from and the orientation towards the robot are also different to the values of the characteristics of the motionings in the leaving episode. These differences could rule out the possibility that any of those motion intervals were neither false positives nor motionings if the characteristics were directly incorporated in the identification process.

Motion Intervals of the Guiding Episodes

The 8% of the motion intervals are compared with the motionings of the leaving episode divided into three paragraphs: similarities to and differences from the motionings and a discussion whether or not the motion intervals are false positives.

Similarities: Motions, which match the motioning categories *step, sidesteps*, *step-back* are found in the guiding episodes. Especially frequent are *step-back* and *sidestep* motion intervals. *Step-back* occur with its corresponding characteristics 'away' (relative trajectory) and 'increase' (relative distance). The pattern ('away' & 'increase') occurred with the relative orientation 'towards' and the relative position 'opposite' in 75% of the cases. The pattern 'opposite' & 'towards' is also a frequent pattern in the motioning in the leaving episode cf. Section 6.5.3 (p.148). In 25% of the cases the position 'diagonal' with the orientation 'away' occurred.

Differences: The newly found relative orientations 'away' is closer investigated. In the beginning of these motion intervals all participants positioned themselves in an L-shape orientation (orienting away from the robot) and changed their orientation during the motion interval to 'towards'. While the participants changed their orientation, their feet executed a slightly different footstep pattern and a body rotation. The body is rotated (about 180°) with the help of two continuously executed steps (a motion with both legs). The body rotation is performed around the own body axis with motion pauses at the start and end. This pattern is not covered by the coding scheme for motionings. Furthermore, there is a major difference in the participant's absolute distance from the robot ($M = 195\ cm,\ SD = 57.4\ cm$). Especially the change of the distance for 'increasing' is different. The average change of increasing distance is 19.3 cm ($SD = 3.7\ cm$). This means that participants took bigger steps back than they did in the leaving episodes ($M = 8\ cm, SD = 11\ cm$) cf. Table 6.9 (p.150).

Discussion of False Positives The guiding episode takes place in a hallway that is why some of the differences in distance might have resulted in the different constraints of the environment. Despite the environmental differences, the situation is similar to the situation in the leaving episodes. In both situations the position of the robot and position of the participant have to change in order to reach the next room. The participant's task was to guide the robot therefore it is safe to assume that the participant's intention is to manipulate the robot's position. However, this time the participants wanted the robot to follow and not to make room. Regarding the overall goal, these motion intervals could be also classified as motionings (true positives) but with another communicational purpose within spatial coordination. The robot's part in with the motioning in the guiding episode was investigated to record what behaviour of the robot had elicited participants to convey motionings. Noticeable is that these motionings occur whenever the robot stops following or has difficulties following the person. The robot Snoopy encountered difficulties driving along the corridor as glass doors provided wrong laser data which led to localisation problems. This situation is comparable to the situation within the leaving episode in which the robot blocked the way and gave the participants a reason to communicate about. Also similar is that the guiding episode is also a very spatially motivated episode as the participants want to reach a physical goal (the next room) and their task was to guide the robot to that goal. At that time the participants did not know what or that something was wrong with the robot. These motion intervals could also be motionings as they might have been conveyed to incite the robot to start following again. To refine the definition about motionings: *motionings are spatially motivated communications which occur when physical goals have to be reached and 'something is not going according to plan' (internal plan) of the person conveying motionings so that the need persists to coordinate oneself in space with the interaction partner, e.g. a robot is standing in the way or a robot does not follow.*

The difference between these motionings and the motionings within the leaving episode are the differences in the characteristic values of the relative change in distance and the absolute distance from the robot. Participants took bigger steps towards and away from the robot. The difference however is not statistically significant when comparing the mean change in distance across all steps. However the mean absolute distance from the robot ($M = 195$ cm, $SD = 57.4$ cm) is statistically different from the absolute mean distance from the robot in the leaving episode (42 $cm, SD = 14.7$ cm) (paired samples t-test: $t(27) = -8.96$, $p < .001$, $\eta^2 = .75$ (large effect)). The relative distance at which the motionings take place is different and can be assigned different zones, intimate and social zone [Hall, 1968]). The motionings which started in the L-shape orientation would be classified as false positives.

6.6.2 Discussion of Changes to the Coding Scheme and the Characteristics

As reported earlier, the relative orientation 'L-shape' is occurring frequently in the presenting episode, and some occurred in the guiding episode. The body is not oriented 'towards' or 'past' the robot but 'away' from the robot. Changing or adding another quantitative value like 'L-shape' would result in a more detailed description of a very specific orientation. However, the actual representation system of motionings could cover L-shape orientations with the 'away' notation similar to values of relative trajectories cf. Section 6.5. Generally, this means that all values of characteristics should be evaluated on the basis of importance or relevance for the interaction partner. To illustrate, there is a difference between trajectories that are 'towards' a person and trajectories that point 'away' the person as the continued motion of 'towards' would 'hit' the interaction partner.

The newly found footstep pattern 'body turn' could be included in an extra section for motioning categories only found in the guiding episode. Adding another motioning category would also result in adding a new characteristic of motionings to the existing characteristics, namely, 'change in orientation' so that the body rotation can be identified as characteristic of a motioning.

The question which naturally follows when adding values or motioning categories to the coding scheme is whether it is the goal of the coding scheme to be generalisable. Adding more values or variables to a relative quantitative system for characteristics of motionings would result in more combinations of values which would in turn result in a more detailed but also more general description of motion in relation to another person. Van De Weghe et al. [2005] and Van de Weghe et al. [2006] stated that in a dynamic scenario entire motion patterns of two moving entities can be represented by the QTC system by adding the characteristic relative velocity and relative orientation the QTC. *But - is that the way for representing motionings?* The motion as such would be completely described by the system but the interpretation that a person wants to spatially coordinate with the interaction partner would be not represented. An approach is to consider the existing QTCs and classify motions of interacting persons (or persons and robots) and investigate whether or not there are patterns of repeating state descriptors, e.g., (+-), (+0), (+-), (+0). If this is the case one could assign a meaning to these patterns. Chapter 8 (Ongoing Research and Solutions to the Limitations)) addresses this approach.

The difference between a system that represents mere motion and the coding scheme (with its characteristics) is that it is created to represent motionings with a similar internal goal or an overall goal, namely, spatial coordination. The goal is *not* to represent all motions but only motionings. There are certain differences compared to the QTCs. The temporal aspect is not considered in the QTCs proposed by Van De Weghe et al. [2005]. This aspect is essential as it describes a central aspect of how to find motionings. In other words, the abruptness of motion is used as means to attract attention (such as hesitation motions [Moon et al., 2011]). The coding scheme for motionings is defined on basis of footsteps. The temporal aspect is important to decide whether the duration of motionings and the pauses are short and therefore abrupt. Furthermore, the absolute distance within one motion is not covered in the QTC. Single footsteps and sways with a pause in motion before and after denote a kind of abruptness by definition. Single steps define a temporal interval and also a specific maximal change in distance (the distance someone could possibly make with one single step). Furthermore, the absolute distance at the beginning of a motioning is not covered by the QTCs. Moreover, different distances have different meanings Hall [1966].

How to find motionings with the existing coding scheme? As already done in the comparison with other motion intervals *the mean duration of a motioning* and *the mean duration of the pause intervals* need to be included in the search for motionings. Furthermore, the footsteps need to be matched and the characteristics need to be compared. As the coding scheme is situation dependent, characteristics of the situation should be handled with caution as these might change. Another issue is the absolute distance between the interaction partners, according to Hall [1966], different distances represent different situations. Therefore the characteristic *absolute distance* indicate another communicative meaning within the spatial coordination situation as found in the leaving episode and guiding episode: 'make room for me' or 'follow me'.

6.6.3 Summary

Regarding Q2 (Section4.1), the results state that abrupt small motionings are used to communicate and can be found with the created coding scheme. The characteristics of motionings, relative distance and relative trajectory, describe the specific motioning categories cf. Section 6.5.6. The characteristics, relative position and relative orientation describe the condition and the motionings compared to other motion intervals cf. Section 6.5.3. But the absolute distance can be used to describe the communicative aspect of motionings. Unfortunately each situation needs to be examined separately but it is hypothesized that situations which have a similar overall goal have also similar motionings. In general, motionings can be found in different episodes but the exact meaning needs to be investigated separately. An idea of how to 'stop' researching all the possible situations before implementing a motioning detection system for a robot is that once the robot has detected a motioning it could ask the interaction partner for its meaning.

Chapter 7

Contributions

In the beginning of this thesis, two questions (Q1 and Q2) were stated which are subject to the goal of investigating the potential of communicative whole-body motion in HRI from the human perspective and from the robot perspective in interaction. These investigations are motivated by a large body of literature in human cognitive research that found out that human whole-body motion is an inherent part of communication. Humans use their whole-body motion to coordinate themselves spatially with others. This works so well because humans can predict motion and attribute intentions to moving entities even if the visible part of the entities is only represented by a dot on a screen. The whole-body motion, which is used to spatially coordinate each other, in other words, which is used to spatially communicate with each other is the topic of this thesis. Narrow places are the environment in the focus because spatial coordination of two interaction partners is most crucial to maintain specific interpersonal distances to each other and to prevent collisions of each other. To do so, the internal plan of each other's motions is interpreted and goal-directed motions are conveyed. The spatial communication via whole-body motion is investigated on the basis of a situation, which occurs frequently in human daily life. This situation occurred also in HRI, especially, when taking the robot out of lab situations into people's homes, namely, the situation that a robot is accidentally blocking the path for the human user or human bystander [Hüttenrauch et al., 2009]. In such a situation, the human needs to spatially coordinate themselves with the robot. That means that she / he needs to somehow communicate her / his intention to the robot. Humans use their whole-body motion to communicate nonverbally in such situations. Therefore, the whole-body motion lies in the focus of this thesis.

To use communicative whole-body motion in HRI effectively both roles in such an interaction are investigated: the robot role and the human role. The robot role is investigated on the basis of different robotic motion patterns and their interpretation by a human interaction partner - a human passerby. The human role is investigated by observing the human expression of communicative whole-body motions towards the robot. This is done to analyse the structure of human motionings.

In this context, two guiding questions are defined in order to explore the potential of communicative whole-body motions and to set the framework for this thesis.

Question about robot motion and human interpretation:
Question 1 (Q1): *To what extent does a human attribute intention to a robot in motion? Considered from the other perspective: which characteristics of robot motion are important to convey the robot's next action?*

Question about human motion:
Question 2 (Q2): *Which characteristics or motion patterns of human whole-body motion are relevant for conveying intention towards a robot? What, in the human whole-body motion, conveys the information to predict the actions or intentions upon which a robot should act? These are the questions of how to find, define and describe human communicative whole-body motion for a robotic system to interpret.*

The next sections answer these questions by proving the definition of motionings and by extracting three heuristics from the large amount of small results provided by the investigations in Chapter 5 and Chapter 6. Furthermore these heuristics are stated to provide practical pieces of advice of how to use the results in current robotic systems in HRI. The question are also answered in detail in Chapter 5 and Chapter 6.

7.1 Definition of Motionings

A motioning is a temporal interval filled with communicative whole-body motion as explained in the coding scheme for motionings. These intervals have characteristics that describe them, delimit them from the group of motionings and from other intervals with different motions. Motionings are abrupt motions of one or two steps or sways, bounded by short pauses and are repeated up to five times.

The different categories of motionings are described by patterns of footsteps as defined by the coding scheme (Section 6.3.1 (p.126)). These categories are summarised to three core categories expressing the direction of whole-body motion relative to the robot: *step_sway* (forward), *side* (sideward), *step-back* (backward).

To distinguish motionings from other similar motions the definition is limited to: Whole-body motions that are conveyed to spatially incite the interaction partner in order to spatially coordinate each other within the shared space. The exact meaning of the motionings are, e.g., "follow me" or "make room for me". These are essential and daily tasks for a robot to master when it is applied in offices and people's homes. Only motionings are considered in which the whole-body motion is the core source of motion when comparing the whole-body to its parts. The 'core source' means that the intensity of the motion of the whole-body is higher than the intensity any motions of parts of the body e.g. co-occurring gestures could have a higher intensity of motion. With this precise definition motionings are not confused with whole-body motions that are means to other motions of parts of the body, e.g. conveying steps to present an item to the interaction partner.

Motionings are defined through their duration of motion and the duration of succeeding pauses in motion cf. Table 7.1 and (Section 6.4.3- Section 6.4.4 (p.139). The short duration and the pauses surrounding the motionings are important because these characteristics represent the abruptness in motion. As in Chapter 5 reported, motions with pauses are better interpreted by participants than continuous motion. Pauses are possible indications to segment actions. This means a pause is an indication for a new action interval that can be newly interpreted and associated with action of oneself cf. Section 2.6 and Section 3.3.1.

The different absolute distances differentiate between motionings for different situations cf. Table 7.1. The interpersonal distances of Hall [1966] help deciding what the meaning of the motioning is and where to set classes of different motionings for different situations in the frame of spatial coordination cf. Section 3.5.

The characteristics, relative position and relative orientation, are condition dependent. This means that already small changes in the behaviour of the interaction partner (robot) influence the human positioning and orientation: in the condition *less blocking* participants chose to position themselves 'diagonally' to the robot and orient themselves 'past' the robot. In the *more blocking* condition two patterns, 'diagonal' & 'past' and 'opposite' & 'towards' were observed cf. Table 7.1.

Characteristics	**Range**	**M**	**SD**	**Group**
Duration of motionings	0.61 sec. - 3.1 sec.	1.45 sec.	0.58 sec.	
Duration of succeeding pauses	0.3 sec. - 6.1 sec.	1.98 sec.	1.9 sec.	long pause
	0.04 sec. - 0.1 sec.	0.07 sec.	0.02 sec.	short pause

absolute distance	M	SD
m. in leaving episode	42cm	14.7cm
m. in guiding episode	195cm	57.4cm

	less blocking		**more blocking**	
ori. / pos.	**towards**	**past**	**towards**	**past**
opposite	—	—	71.4%	28.6%
diagonal	13%	87%	28.6%	71.4%

P	**characteristic**		**motioning category**		
	distance	**trajectory**	**step_sway**	**side**	**step-back**
1	increase	away	–	12.5%	87.5%
2	decrease	past	85.6%	14.3%	–
3	decrease	towards	77.8%	22.2%	–
4	no change	towards	45.5%	55.5%	–

Table 7.1: *A condensed overview of important characteristics for the definition of motionings cf. Chapter 6 for detailed information.*

Furthermore, the characteristics, absolute distance, relative orientation, and relative position describe the beginning of motionings and therefore the initial situation from which the motioning starts cf. Table 7.1. These characteristics change depending on the spatial coordination situation.

The characteristics relative distance and relative trajectory are characteristics that form patterns and describe the specific motioning categories cf. Table 7.1.

7.1.1 Discussion

The motionings are defined for human motionings in interaction with a robot. There are certain limitations when transferring these motionings to a robotic system. Direct side motions and swaying of the body are not possible for the robots presented in this thesis cf. Section 6.1.3 and Section 5.1.4. These robots do not have a holonomic drive and have a static body that cannot or at least should not sway. On-going research of how to transfer and prototype whole-body motions for a robot is presented in Chapter 8. Furthermore there are discrepancies between the interpretation of robotic motion and the actual wish of the participants of how a robot should behave cf. Section 5.3 so that just transferring human motioning to robots is not advisable.

7.2 Three Heuristics for The Practical and Actual Use of the Results for Robots

This section summarise the results of this thesis investigations to three heuristics of how the results can be used in the actual HRI. These three heuristics or pieces of advices result from the investigation of the potential of communicative whole-body motions in HRI and show that communicative whole-body motions are part humans in interaction with the robot. Therefore, they should be used to equip the robot's communicative ability with a new and natural means of communication to make HRI more acceptable and smooth. These heuristics are: The robot should represent and detect motionings and ask for its meaning; the robot should be aware of its own motion; the robot needs to convey the goal of its motion or action. These heuristics are explained in the following.

Consideration of human motionings The coding scheme for motionings with the additional description and definition of characteristics enables roboticists to build a system that detects motionings. Human motionings are conveyed in spatial coordination situations with the robot and need to be considered to make to the interaction naturally and intuitively acceptable. Motionings can be detected but the exact messages are not easily interpreted without any situation awareness unless they are conveyed in guiding or leaving episodes because these were investigated. If the exact message of a motioning is unknown, the robot would be at least able to detect that someone wants something (that the human tries to attract attention). The exact message of motionings depends on a large number of different variables, e.g. context of the situation, attitude towards the robot etc. cf. Section 3.6. This is why a heuristic is suggested that whenever the robot detects a motioning and the message is unknown to the robot, the robot should ask for explanations. As Fong et al. [2001] states, humans and robots should work as partners, this also includes asking for help, especially, when the robot detects something it cannot cope with. Also Rosenthal et al. [2011] reported that their robot asks for help when there are obstacles in the paths of the robot and it cannot fulfil its tasks. *Asking for explanation or help* is a heuristic to cope with the mass of interpretations of situations which the robot does not have the knowledge about. As Birdwhistell [1970, p.173] stated on body motion " [t]he meaning of such behavior [body motion] is not so simple that it can be itemized in a glossary of gestures."

Awareness of own motion A result of this thesis is that abrupt robot motions will be interpreted whether or not they are intended to communicate a certain message. Especially, pauses of motions help people to segment motions and associate the meaningful segmented motions with their own motions. Therefore a robot should have an awareness of its own motions. Not only human motionings but also the own robot motionings should monitored by the robot. A robot does not work free of errors. Sensory data can be erroneous and pauses of motion can be the result (Section 5.3.7 and Section 6.6.1). Therefore, when robotic motions are performed, which are similar to motionings, and which have not been planned to be motionings, the robot needs to explain itself to stop human interaction partners from attributing intentions to the conveyed motion, e.g., a wheel of a robot gets caught and the robot drives to the left and stops, then drives to the right, and to correct the paths it drives to the left again. It has been identified that, in particular, stops of motions are interpreted cf. Section 5.3.7 and that small and short motions are used from humans as communicative means cf. Chapter 6.

Expression of the goal The legibility of the goal or internal plan of robot needs to be emphasised as third heuristic. Humans are well able to interpret, predict and infer intentions from complex social goal-directed motion even if the motion is abstracted to single dots cf. Chapter 3. Inferring the goal of robotic motions was an important issue in the questionnaire in the Study on Robotic Motion Patterns cf. Chapter 5. Participants suggested to install indicators (like on cars) on the robot. Installing indicators on the robot is a way of representing the overall goal of the robot for the human interaction partner so that the motion even if it is erroneous can be anticipated. For that reason, Shindev et al. [2012] created a robot that projects arrows on the floor in front of the robots to indicate direction of motion of the robot. Presenting the goal of the motions increases the legibility of the robotic motions. This in turn may help interacting persons to disregard small misleading motions.

7.3 Conclusion

To conclude this chapter, motionings are abrupt motions conveyed with the whole-body. In humans, these motions include of one or two steps to the side, front, and back of the person but also can consist of body swaying and body turns achieved by one or two steps. Their duration range from 0.61 sec. - 3.1 sec. and are repeated up to five times per communicational aspect. The motionings stand out compared to continuous motion because pauses occur directly around motionings and separate them from other motion intervals.

These pauses can be very short about 0.04 sec. - 0.1 sec. or slightly longer 0.3 sec. - 6.1. sec. cf. Table 7.1. The investigations have identified that pauses within motions are a reason why participants are interpreting robot motions. Pauses in motion enable humans to segment robot actions and associate these with the action of themselves cf. Chapter 5. This finding is supported by findings of related research: a pause can be an indicator for a new action cf. Section 2.6 and Section 3.3.1. Combining this knowledge with the findings of the Gestalt principle, temporal succession, pauses of motion can turn into effective means of communication cf. Section 3.1.2.

Actions, which happen subsequently, are easily interpreted to have a cause - effect (causal) relationships. As a pause in the motion of a robot is an indicator for a new action which an approaching human can easily relate to the own action, e.g. in this context attributing an 'effect' into the robots motion is performed in this way: I walked along this corridor (cause), and because of my presence the robot moved the way it was moving (effect).

The research within this thesis has been conducted to investigate the potential of communicative whole-body motions, in particular, in situations in which spatial coordination is necessary. This thesis displays that human and robotic whole-body motions play a powerful role in nonverbal communication because the expression of communicative whole-body motions is a natural way for humans to spatially coordinate with each other and in interaction with robots. In addition, humans convey these communicative whole-body motions whether or not the robot has the ability to be responsive to this kind of communication. Investigating human and robotic whole-body motions makes another piece of the complex human communication available for HRI. There is not only the conveying part of humans in an interaction but also the interpreting part of information. Robots convey motion patterns, which are interpreted by human bystanders and users, whether or not they were originally planned. That means that it is not only a challenge to interpret (detect, represent, infer message) human motionings with a robotic system but also it is a challenge for a human to interact with the robot because she / he is misled by interpreting erroneous robotic motion which was not planned to communicate. Therefore and with the knowledge that motionings are a means of spatial coordination a robot should...

a)*Consider human motionings* and ask if the message of the motioning is not legible for robot.
b)*Be aware of misleading motions* produced by its own way of moving and explain itself to make its motion legible to the human.
c)*Express goal-directed motions.* Robots, which are not free from misleading errors (jerky motion / pauses) need an additional aid to make their motion legible and more goal-directed for the human to interpret. Car indicators have been suggested by the participants of the RMP study conforming with the advice producers of animation films and actors give: "everything needs to be exaggerated to be legible by the audience to rule out the interpretation of double meanings" cf. Section 3.3.1.

Figure 7.1 provides a final overview of this thesis' methodology, investigations, and their results.

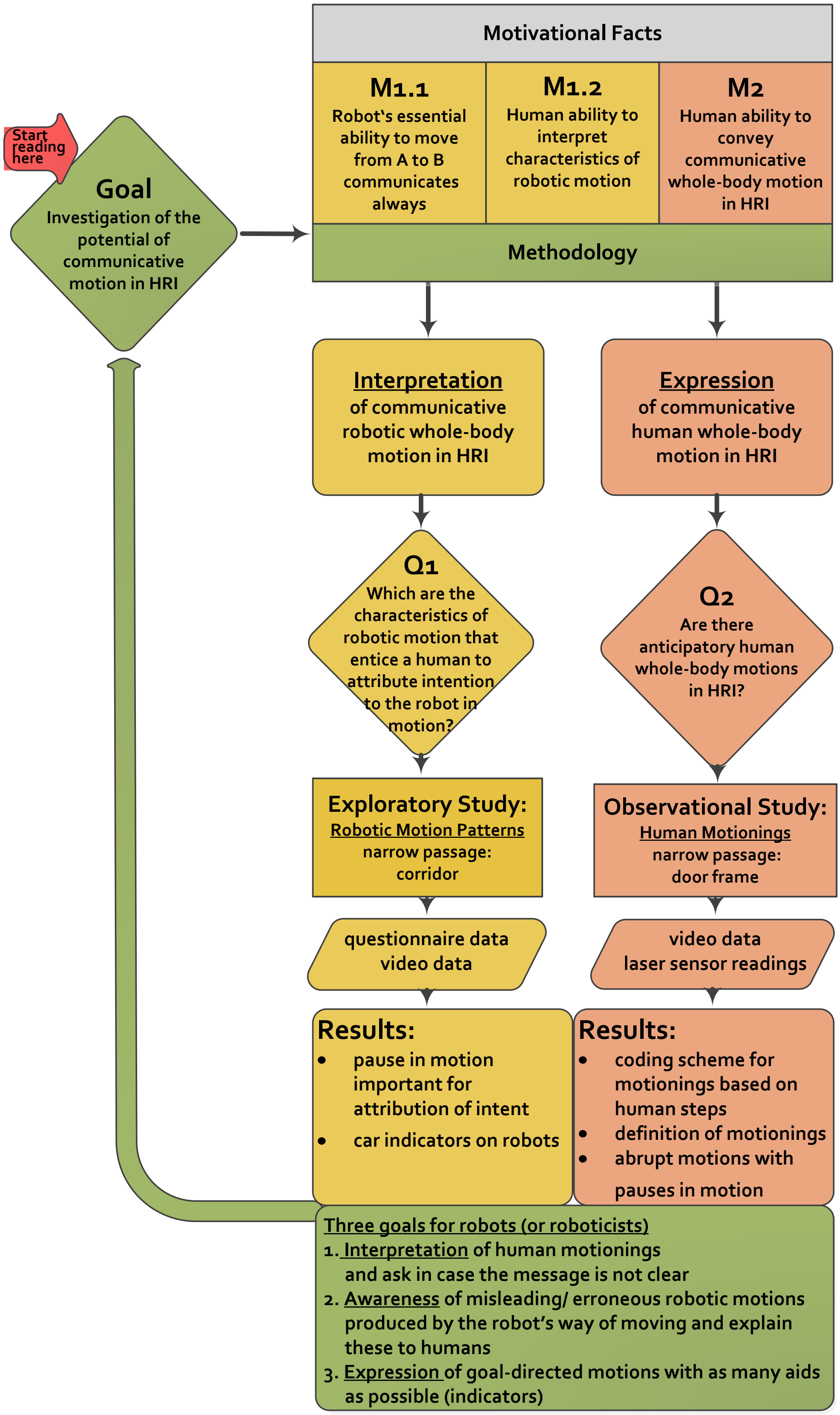

Figure 7.1: *This figure displays a summary of this thesis' methodology, investigations, and results as described in this thesis.*

Limitations of the Investigations The investigations in this thesis are conducted with Germans and Swedes. Therefore there are certain limitations to the scope of the interpretations of the results. With the words of Birdwhistell [1970, p.81] “[a]lthough we have been searching for 15 years we have found no gesture or body motion which has the same social meaning in all societies”, this means that there are cultural differences which need to be regarded. For now there is no solution to that limitation. For all others there are solutions.

A limitation of the scope of this thesis is that the explicit design of robot motions is not considered. However, profound research on the basis of my results has already begun. Therefore an entire and final Chapter addresses the limitations of this thesis. Three solutions are presented to provide different approaches to the question of how to design and prototype 'naturally' interpreted robot motions cf. final Chapter "Ongoing Research and Solutions to the Limitations“.

Chapter 8

Ongoing Research and Solutions to the Limitations

This chapter presents two limitations of this thesis and provides solutions documented by my own current research. In the following, the sections present already initiated approaches and outlooks of how to cope with the limitation of this thesis.

This thesis investigates not only the robot's role of conveying motion and the interpretation of this motion but also it investigates the human role of conveying motionings. Naturally, there are limitations on both investigations. The first limitation is that only the human motionings are analysed on the basis of the QTC. The QTCs proposed by Van De Weghe et al. [2005] contain the potential to represent motions of both interaction partners in one representation. The second limitation which this thesis does not cover, so far, is the explicit design of motions. In three new approaches, methods are presented to prototype robot motions and provide a way to investigate the interpretation of these designed motions.

8.1 Qualitative Trajectory Calculus

The whole-body motions conveyed by the participants in the Human Motioning Study (Chapter 6) were analysed on the basis of the Qualitative Trajectory Calculus (QTC_c) proposed by Van De Weghe et al. [2005] cf. Chapter 3.4.3. Only the human part in the interaction was analysed because the robot part in that interaction was stable.

The robot was not moving. However, the Qualitative Trajectory Calculus (QTC_c) was proposed to represent two moving objects in space, namely the change between two successive points in time. The representation of the trajectories of each interaction partner provides the general pattern of the motion in the interaction. Especially, in more dynamic situations in which both interaction partners are moving, this is helpful to receive an overview over different or similar ways how two interaction partners are coordinating their bodies in space. The analysis of human and robot motions in interaction with each other applying the (QTC_C) is currently advanced[1] on the basis of the data of the Robotic Motion Patterns study cf. Chapter 5.

8.1.1 QTC in Spatial Interaction of a Robot and a Human

The video data of the robot and the participant in the Robotic Motion Patterns study (Chapter 5) serve as basis for applying the QTC_C. The existing video annotation (Section 5.1.6) is transferred into the QTC_C version with the help of the SALEM Toolbox automatically [Hanheide et al., 2010]. So far the motion patterns MP 3 and MP 4 (Section 5.1.5) are investigated for description of motion patterns. Within MP 3, the robot stood still in the middle of door frame as the participant turned into the corridor and then drove towards the person and to its right side and progressed along the side. Within MP 4, the robot stood still in the middle of the door frame as the participant turned into the corridor, and then drove towards the person and carried on driving in the middle of the doorway. Each trial in these conditions MP 3 and MP 4 was translated into five to eight QTC_C representations (state descriptors). Each representation corresponds to a state. This means that each state consists of a four-tuple (e.g.'+-0+'), which represents the direction of motion (trajectories) in two directions (sideways and towards - away) for each interaction partner cf. Section 5.1.5 for a detailed description of the QTC_C. Thus, the entire MPs of the participant and the robot result in a sequence of four-tuples of state descriptors. The most probable sequences of those four-tuples are computed by modelling a Markov chain for each MP across the data of all participants in that MP. Subsequently the most probable path through the Markov chain is computed cf. [Hanheide et al., 2012]. Consequently, a Markov chain can be modelled by observing the QTC_C states and computing transitions between these states[2].

[1] In cooperation with Marc Hanheide and Nicola Bellotto both with the School of Computer Science at University of Lincoln, England [Hanheide et al., 2012]

[2] This is possible because the sequences have a definite start, an end, and a finite set of QTC_C states as the data results from finite real world data cf. [Hanheide et al., 2012]

Preliminary results show that the actual passing of the robot and the human are similar but the behaviour of the robot and the participant before they pass each other is different. This result reflects the different motion patterns of the robots and consequently different spatial behaviour of the participant as well. This supports the results of the questionnaire analysis in Chapter 5.3. Research about how to detect and how to interpret human whole-body motions on basis of my descriptions has been already initiated [Hanheide et al., 2012]. Furthermore, Bellotto [2012] reported initial work on a system for robots that turns quantitative data of robotic sensors into qualitative concepts based on a different version of the QTC_{B2} cf. also [Van de Weghe et al., 2006]. As criticised earlier, certain information is missing the interaction to build heuristics of how to interpret communicative whole-body motions. This analysis has shown that the QTC's are a promising start to receive a general overview over the interplay of entire motion patterns. Next steps include merging the proposed QTC's (trajectories, distance, speed) and the absolute values suggested in Section 6.6 to one qualitative framework. Subsequently more information is added e.g. orientation and position. Adding more information to the QTC will result in a complex but sound reasoning system which nevertheless needs to be collapsed as many of those states can be summarised in the way it is done in Chapter 6.5. As stated in Section 6.6, next analyses should consider absolute distances between two interaction partners and temporal information about the duration of QTC states. The absolute distance can be interpreted on the basis of social conventions such as different interpersonal zones. With the help of these absolute values, it is expected to come closer to a representation of the meaning of communicative motions in HRI (in contrast to a mere representation of moving entities in space). Furthermore, next steps include analysing the remaining motion patterns of the Robot Motion Pattern Study (Chapter 5) with the new QTC and combining the coding scheme for motionings with the QTCs. The reason for collapsing and expressing quantitative motion data of social interactions is the goal to make the message behind motions legible not only for humans but also for robots which need to take part in our daily spatial interactions when applied in households and offices.

8.2 Design of Robot Motions

Throughout this thesis it has been argued that motions of humans, objects and abstracted versions of both, convey clues about character, social role and intent. The line of thought is that motion is a powerful communicative means. Even simple translational and rotational motion of a robot should be explicitly used as communicative means, due to the fact that humans are able to attribute or detect the intention behind motion, having only a few clues to infer from.

Nakata et al. [1998] states that human participants carefully watch the physical motions of robots. Furthermore, they suggest that robots should be designed to send the right messages to the people around them. The explicit design of robot motions is a topic, which this thesis has so far not explicitly mentioned. The results of my studies provide some answers of how robot motion should be designed, namely with abrupt with pauses to make action segmentation and interpretation easier. There is always the challenge to design communicative motions for a mechanoid robot on the basis of communicative motion in human-human interaction or human motion in human-robot interaction. Human motion can inspire the design of robot motion but there is always the challenge in the transfer [Dautenhahn, 2007a].

So far robot behaviour for social HRI is designed on the basis of either human-human interaction or human-robot interaction or both or by designing robot behaviour and evaluating and advancing it in an iterative process.

Although these approaches have certain disadvantages they have one goal in common: These approaches try to find a way to design robot behaviour legible for human interaction partners. That means that behaviours of the robot should be directly understandable for the human interaction partner. Moreover, they should – like human behaviours be – "intuitive" so that humans can predict, interpret them and develop a kind of tacit knowing or foreknowledge about the robot's goals.

Mechanoid robots, such as BIRON and Snoopy, have, compared to humans, less degrees of freedom for their rotational and translational motion. In fact these robots can implement abrupt motions with pauses but are limited when it comes to direct sidesteps for making room for other people in abrupt and fast way. Human steps to a side, can be abrupt and are suggested from 31.8% of the participants in the Robot Motion Pattern Study as acceptable passing by pattern when avoiding a robot in a corridor, cf. Section 5.3. Furthermore, sidesteps are used as a part of the human communicative whole-body motions repertoire (motionings) cf. Chapter 6.3. One or two steps generally in any direction are important means of human motionings.

The results of this thesis and related work state that robot motions are interpreted by humans and that humans are communicating via whole-body motions with a robot whether or not the robot has the ability to detect and interpret these or act in the same way, research in the field of communicative motions in HRI scenarios should be subject to ongoing research. Therefore, further research with the general aim to design robotic communicative motion has been already initiated or is planned. In the next section, three approaches of how to prototype robot motions, which communicate in a legible way, are presented. These approaches cope with the presented limitation in different ways.

8.2.1 Creating Intuitive Robot Motion

This idea uses the approaches to find a way to design intuitive motion by looking at the ways humans behave or would behave. This time it is neither exclusively human-robot interaction nor human-human interaction which is the model. The idea is to let human participants of a HRI study steer the robot in the way they would imagine themselves to behave spatially and in the way they would want a robot to behave spatially. This idea is also inspired by the very common way of conducting a study in HRI: the Wizard-of-OZ (WoZ) technique as it is a very efficient method of prototyping behaviours or evaluation distinct HRI situations without a fully functioning robot [Dautenhahn, 2007a]. It is a method of steering robots in a comparable way in each trial. However, in this approach it is expected that the naive participants, steering the robot, display their own version of motion patterns. The following study which implements this idea and is already conducted[3]. The goal of the study is to receive patterns of whole-body motions of how a robot should cross a person's path. The robot and the human need to negotiate with each other how to cross each other's paths. In the following paragraphs, the study on *HRI Crossings* is briefly described and preliminary results are presented cf. [Lichtenthäler et al., 2013].

[3]The study has been conducted in cooperation with my colleagues Sascha Griffiths who is also with the CITEC (Cognitive Interaction Technology - Centre of Excellence) at Bielefeld University and Christina Lichtenthäler who is with the Human-Centred Artificial Intelligence Group at the Technical University Munich

Figure 8.1: *The picture presents the dimensions of the crossing area and the setup of the shelves. The shelves and the storing place were set up in a way that the confederate, who played a customer and the robot would coincidentally cross each other's way in* 45° *and* 90° *angles. The picture displays the VICON cameras on tripods. Boxes in the middle of the area present the obstacles for the practise of the participants before they started a trial. These are removed for the actual trial.*

Setting - Equipment The study was conducted in the Biomechanics Lab of the Neurocognition and Action Group (Prof.Dr. Thomas Schack). This lab is approximately $133m^2$ wide, which left enough space for us to set up a pseudo shop with shelves and storing place. The area in which the actual crossing of paths took place was 4 m x 5 m wide and surrounded by 10 VICON (6 x T10, 4 x T20) infrared cameras[4] for 3D motion tracking and a camera which recorded in HD quality cf. Figure 8.1. The robot and a confederate (experimenter) were equipped with a rigid body[5] marker each for the purpose of motion capturing and the computation of the orientation of both. The robot BIRON was used as the mobile service robot.

Recruitment of participants The participants in the study were recruited via email inviting them to get a robot driver's license which they received at the end of the study. The participants were mostly employees of the Bielefeld University.

[4] `www.vicon.com/products/cameras.html`

[5] We used rigid bodies (VICON tracking markers) constructed by Bernhard Brüning and colleagues, cf. [Pitsch et al., 2010]

Scenario The participants of the study were told the same cover story about a shop that thinks of using a robot to transport goods from the storing place to the shelves. The participants are asked to help the robot navigate from the storing place to a shelf. Furthermore, they were warned that robot might encounter customers. For this task the participants received an introduction to the robot BIRON and an extensive practise of how to steer the robot via a wireless keyboard. Only after the participants managed to drive around the obstacles (boxes) and felt capable of steering the robot, the trial began.

The commands of how to steer the robot were marked on a keyboard with arrows. Five keys corresponded to the five ways of moving the robot: straight forward, rotate around its own axis in a clockwise direction, in an anticlockwise direction, drive and turn left or right in an arc. The robot only moved by holding down the particular key and the robot stopped by relieving the key. These motions map the actual ability of the robot BIRON to move. There was no possibility to accelerate the robot as it was driving at its full speed of 0.7 m/s.

The robot had the task to carry one item (of 15 items) at a time from the storing place to the shelf. The storing place and the shelf were approximately 10 m away and opposite of each other cf. Figure 8.1.

A confederate had the task of walking to different shelves and putting items in her / his basket in randomised different angles and speeds. Furthermore the confederate wore sunglasses to stop eye contact with the steering participant. The shelves were arranged in a way that the robot and the confederate would coincidentally meet each other in 45° and 90° angles. These meetings were produced only by accident as the confederate had to walk at different speeds (slow, normal, fast) without stopping or accelerating. Furthermore, the confederate had to visit different shelves in a predefined and randomised order.

Two other experimenters helped to sort and put away the goods onto the robot and into the shelf as the robot had no arm and we did not want to distract the participant or ask too much of the participant. A minute was written for each trial describing the observed motion patterns. The entire trial was no longer than 20 min. After each trial one of the experimenters asked questions in an interview on the basis of a questionnaire. The demographic results were recorded within the interview. Furthermore, there was one open question asking whether the participants were missing anything or found something odd when controlling the robot.

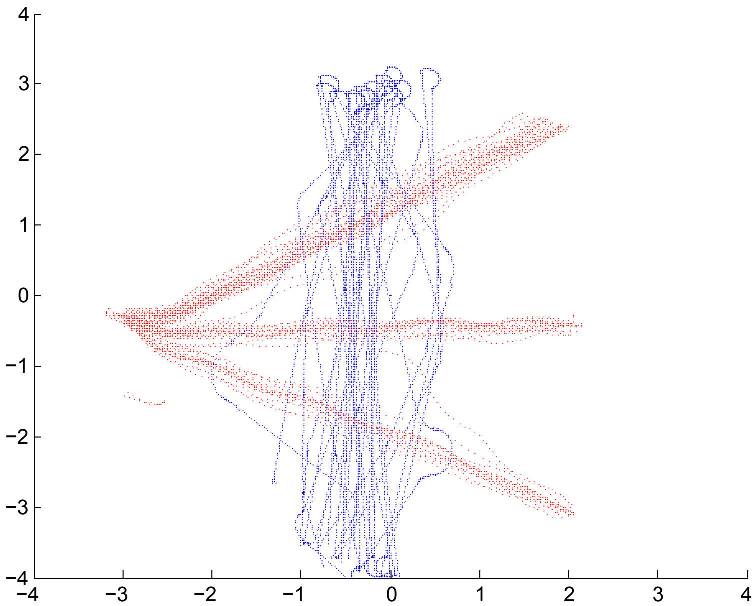

Figure 8.2: *This figure presents a plot of all paths of one participant and BIRON recorded by the VICON cameras. The blue dots represent the robot's positions (motions) and the red dots represent the experimenter's position (motions) over the time of the trial. The axes represent metres originating from the middle of the tracking area.*

Preliminary Results 47 participants (55% f, 45% m) took part in this study. Their educational background was mostly in humanities. Furthermore, 98% of the participants had no contact to robots during their work, especially not with BIRON. Further preliminary results are based on 35% of the participants and a first overview over the video -, VICON data, and for control the experimenters written minutes for all 47 trials. The following motion patterns of the robot steered by the participant took place and are counted disregarding the angle or speed at which the crossing took place. The participants steering the robot had to think of a strategy how to cross paths with the human without colliding in approximately 400 incidents. Exemplary, Figure 8.2 presents the data of one participant.

The preliminary results of the observed actions can be summarised to the following points. The list presents all actions the participants conducted while steering BIRON cf. Figure 8.2:

- stopping of the robot observed in 69.9%[6]
- stopping and driving (stuttering) of the robot, observed in 18.6%
- nearly crashes 5%
- avoiding by starting to drive a curve 4.3%
- driving over the feet of the confederate 2.2%

The motion pattern, which the participant performed the most while steering BIRON, was driving straight towards the goal (shelve or storage place) and stopping when the confederate came approximately 20 cm - 100 cm close to one of the sides or front of the robot. Each participant performed this pattern during crossing situations in $60\% - 95\%$ of the cases. All participants had a similar strategy to find a pattern which they kept performing most often, when comparing the course of crossings per trial. First they were steering BIRON straight to the respective goal, when the first crossing occurred, they tried a few patterns (1-3 times) and then used the stopping pattern for most of the crossings, and / or repeated different patterns. The stopping behaviour was displayed the most by all participants.

Discussion / Conclusion The stopping pattern lines up with the results of the studies presented in this thesis so far (Chapter 5 - Chapter 6). From the communicative point of view, stopping the robot will result in an abrupt end of the motion. In addition, the second most frequent pattern stopping and driving in a row (stuttering) fits to abrupt motions as well. The abrupt motions attract attention and highlight to the human crossing the path with the robot that the robot will yield. From the efficient point of view, the stopping and the stuttering pattern are the patterns with the least effort: the participant, steering BIRON, does not need to anticipate when the human will get in the way of the robot – the participant stops BIRON or slows BIRON down when the human is close[7]. Therefore, the participant does not need to deviate from the course she / he has planned for reaching the goal. As the goal is straight ahead every curve would mean a deviation from the course. This result corresponds to the questionnaire results of the Robot Motion Pattern study in which the participants rated a stopping behaviour as avoiding behaviour. This pattern is an

[6]These percentages are computed on 35% of the data and compared with the written minutes for each trial.

[7]The exact closeness needs to be determined

interesting way of reducing the steering effort and the effort to predict the motion of the confederate walking from shelve to shelve. This pattern is also interesting as we made sure that people were perfectly fine with driving curves around cones without getting lost or stopping. However, when we asked at the end of the study most people wished for accelerating and decelerating functions on the keyboard. We had restricted the way of steering because the robot was at its highest possible speed. More acceleration would have resulted in an unstable way of driving the robot as the robot's mass centre is high and could resulted in a fall of the robot. Nevertheless, safe deceleration and acceleration mechanisms for a robot would open up new possibilities for motion patterns that appear natural and would result in the robot not needing to replan its path. The only question which remains and which will be hopefully answered by reviewing the full data and all aspects of the data is the question when should a robot accelerate and when decelerate? To receive motion patterns in the way it is presented in this study is a new way of prototyping behaviours in hands on sessions in which the participant is close to actual event but restricted to the way a robot functions or in this case navigates.

In the next section another way of prototyping robot behaviour is presented.

8.2.2 Transferring Human Wheelchair Motion to Robots

This idea approaches the challenge that a robot does not have as many degrees of freedom in its movement as humans do. To design robot communicative motions from human communicative whole-body motions poses the challenge of having to transfer higher-dimensional motion to less-dimensional motion without confusing the message behind the motion. A human step to the side consists of one motion in the direction to the side with one or two feet from the human point of view as opposed to robots like BIRON and Snoopy[8], which are not capable of driving to the side. These robots need to turn on the spot, then drive and turn to the starting orientation again or they can drive a curve backwards and forwards again to reach the exact spot a human would reach or if the robot would know before that it has to reach a position 20 cm next to its plan path it could start planning a new paths. These examples display that the transfer is not easy. These examples would either present many possibilities for a human interaction partner or passerby to predict a different direction of motion of the

[8]Both robots are from Adept MobileRobots and used frequently by other researchers in the field of HRI [Hüttenrauch et al., 2009; Walters et al., 2011]

robot or would need future information the robot does not have. The idea is to take people who use a wheelchair as interaction partners in HRI studies and to observe two wheelchair users in interaction. Wheelchair users have approximately the same degrees of freedom. These motions are easier to transfer to human users. This field of research would not only be interesting for transferring data of human wheelchair users to robots but also for wheelchair users who are incapable of driving their wheelchair on their own cf. [Galluppi et al., 2008]. Galluppi et al. [2009] presented a wheelchair that takes over for the wheelchair user whenever she / he says so.

8.2.3 Prototyping Motion through the Interpretation of Robot Motion

This approach is inspired by the outstanding ability of humans to interpret all kinds of abstract motions which first was reported by Heider and Simmel [1944]. The results of human interpretation and attribution of intention to the robot by watching designed robot motions is the idea of the approach. The approach introduces a new way of designing robot motions in a legible way to the humans (as the humans took part in the design process). Furthermore the approach uses the actual robots in question, so that no transfer to similar but different robots need to take place. The following description of an idea is based on my proposal for a CITEC research grant which was successful. Furthermore, it provides the basis for further research grant proposals. This proposal is based on the related work stated in my thesis, cf. Chapter 3.1. The next paragraphs provide a short summary in which the idea is proposed. Heider and Simmel [1944] were two of the first researchers to find evidence that 2D motion of abstract objects (circles, triangles) together on a white background is enough information for humans to attribute character, motive and intention to these objects. In their experiments 34 participants had to watch a film with simple geometric objects moving around. Afterwards they had to narrate what they had seen. All participants considered these objects as animate creatures and ascribed a motive to these objects.

These experiments were repeated in similar and modified ways to find important features of situations or cues for entire motion signatures cf. [Heider and Simmel, 1944; Barrett et al., 2005; Berry et al., 1992; Springer et al., 1996; Castelli et al., 2000; Crick et al., 2007]. These authors have shown that the characteristics of mere motion are responsible for having attributions of intent. Furthermore, they identified that the temporal succession of events and spatial proximity of the objects is important when interpreting or making sense of motion of objects. Moreover, speed of moving objects was also considered to be a salient feature of the situation, cf. [Heider and Simmel, 1944; Barrett et al., 2005]. These results fit perfectly well into the line of research of my thesis.

This proposal is also based on the key statement of this thesis motivation provided by Barrett et al. [2005]. The authors state that "whole-body motion is a reliable, valid, and easily perceived source of information about intentions because different kinds of intentional action have different motion signatures" [Barrett et al., 2005, p.313].

The idea is to transfer the mentioned methods of Heider and Simmel [1944] and Barrett et al. [2005] of how to investigate whole-body motion cues to HRI. This is motivated by the fact that humans are able to interpret simple motion trajectories of objects abstracted from human appearance.

Instead of animated objects or point clouds participants are going to watch two robots moving around in a recorded video clip. These robots would display certain behaviours, e.g. passing by each other, playing a game of tag. Those robots could display similar stories to the one Heider and Simmel [1944] presented to their participants cf. Section 3.1.1. The participant's interpretations of the observed scene is then used to find out to what extent the motion of the robot in question will be 'understood'. The way how the robots move (smooth - jerking motion) and the time (when a motion follows the next motion) can be alternated to find different extents of attributions.

Resulting research questions within this line of research are: Are humans interpreting goal directed motions (Heider and Simmel and Barrett style [Barrett et al., 2005] cf. Section 3.1.1 and Section 3.4.1) of two robots in a similar way? Do humans attribute robots social role and intent to the robots as well? To what extent do humans attribute a Theory of Mind (ToM) to robots? What cues are needed so that human users are able to have a ToM of the robot - so that people are able to expect and predict robot motions?

Research is started with the interpretation of motion of mechanoid robots. Mechanoid robots do not have the appearance of humans. This poses an advantage when the communicative potential of motion is investigated as human-like features need to be controlled or excluded. By excluding human-like features it guaranteed that these features are not interpreted. Therefore mechanoid robots, like BIRON and Snoopy, are good tools of advancing the research of the communicative potential of motion signatures which this thesis laid a basis for. Furthermore, displaying only robots not human-robot interactions makes sure that participants interpreting the scene would not use the human motion to infer intentions.

This idea investigates the human part of understanding the robot's action and is used to follow up questions posed in this thesis. The new method is a way to identify characteristics of motion for state-of-the-art robots like BIRON. Questions which arose during research for my thesis can be treated and results of my thesis further elaborated: Which characteristics will be reliable to use in interaction (e.g. abrupt motions) and to what extent are jerking motions of a robot confusing for a human user? The temporal succession of events is crucial to causally connect events. How much time can lie between two events till they are not considered to be connected anymore?

With this new method one is able to research only one characteristic at a time without depending on speech recognition or consistent cover stories around the study topic. Different robots can be investigated on the basis of this method as it makes trial data highly comparable.

8.3 Conclusion

This chapter presented on-going research which I conducted on the basis of this thesis's results. Further research of using the QTCs to classify patterns of joint behaviour has been presented. Furthermore three approaches of how to prototype communicative robotic motions were explained. These approaches vary in their methods to cover different initial points of how to design robot motion for social robotics:
Prototyping robot motions through naive wizard-of-oz who impersonates the robot while steering it through HRI situations.
Prototyping robot motion through observing human wheel-chair motions in situations similar to HRIs to make the degrees of freedom of the directions of motion comparable.
Prototyping robot motions through human interpretations of video clips showing robot motion patterns.
The goal of chapter was to show that advancements in the field of communicative whole-body motions have been already initiated and that it is a current topic of HRI's research. This thesis emphasises that considering the communicative potential of whole-body motions in HRI is an essential topic of research for producing smooth interactions.

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Appendix A

Notations for the Statistical Analysis

Notation	Explanation	Author
N	total sample size	
n	partial sample size	
M	mean	
SD	standard deviation	
Md	median reported for ordinal data or when there is a high variation in the data	
IQR	Interquartile range represents the middle 50% of the data (25% of each side of the median). IQR= 3.Quartile – 1.Quartile. Data points which are outside the 3 times the IQR are considered to be extreme outliers	
Kappa (Cohen's)	Measure of agreement to asses inter-rater agreement moderate agreement =.5, good agreement >.7, very good agreement =.8	Pallant p.224 (Peat, 2001, p.228)
α	significance level is set to $\alpha=.05$ but as the exact p-value is reported, the significance level can be read from the p-value. If $p<.05$ then the test is significant (H_0 is rejected). (Some test are reported differently, if this is the case it is emphasised in the text)	
df	degrees of freedom	
p	probability, here it is the significance level. The exact value is reported. Only if $p=.0001$, then $p<.001$ is reported.	
z	Mann Whitney U value for N>30	
U	Mann Whitney U value for N<=30	

Figure A.1: *This figure presents the notation of mathematical and statistical abbreviations and their explanations according to Pallant [2010]. 'Pallant', a page number, and another citation are explicitly stated in the third column whenever Pallant [2010] cited someone else.*

Effect Size	Explanation	Author
effect size	In general, the effect size is the strength of the difference between groups which have significant differences. It is a value that indicates the degree to which the variables are associated with one another. A large effect supports the decision to reject H_0 (there are no differences between groups) if the statistical test presents a significant difference. The effect size contributes to the power of a statistical test.	Pallant p.210
r	effect size (Mann Whitney U), $r=\lvert z/\sqrt{N}\rvert$, low effect: $r=0.1$, medium effect: $r=0.3$, large effect: $r=0.5$	Field p.532
η^2	eta squared ranges between 0 and 1 This effect size statistic provides an indication of the magnitude of the differences between your groups (and tests whether the difference could have occurred by chance) effect : small effect = .01, medium effect = .06, large effect = .14 $\eta^2=t^2/(t^2+(N1+N2-2))$	Pallant p.210 (Tabachnick and Fidell 2007, p.55) (Cohen, 1988)
η^2 for paired t-test	eta squared ranges between 0 and 1 This effect size statistic provides an indication of the magnitude of the differences between your groups (and tests whether the difference could have occurred by chance) effect : small effect = .01, medium effect = .06, large effect = .14 $\eta^2=t^2/(t^2+(N-1))$	Pallant p.247 (Cohen, 1988 p.284)
C_{corr} by Karl Pearson, here always corrected	corrected contingency coefficient, measurement of association of nominal data: $(0\leq C_{corr}\leq 1)$ close to 0 : no effect or association, close to 1: strong effect or association effect size for χ^2 here it is also used for the Fisher's exact test. This measurement serves as indication, it is stated but not explicitly considered in the text. $r=row$ $c=collumn$ $C_{max}=\sqrt{min(c,r)-1/min(c,r)}$ $C_{corr}=\sqrt{\chi^2 min(c,r)/(\chi^2+N)(min(c,r)-1)}$	Ostermann

Figure A.2: *This figure presents the notation for effect sizes and their explanations according to Pallant [2010]. The third column: 'Pallant' and a page number denote that the explanation is quoted. 'Pallant', a page number, and another citation in brackets '()' denote that Pallant [2010] cited someone else. 'Ostermann' and 'Field' are stated to denote that the notation or explanation is cited from Ostermann and Wolf-Ostermann [2005] or Field [2005].*

Statistical Tests	Explanation	Author
Fisher's exact test	$value = 18.7$, $p = .003$, $C_{corr} = .88$ explores the relationship between two or more categorical variables and compares frequencies. Better test for small sample sizes than . As the sample size is at the threshold for using χ^2 the Fisher's exact test is presented but the effect size C_{corr} is presented. Effect size for χ^2 : C_{corr} these values are only indications of the effect the statistical test has if it would have been a χ^2 test.	Ostermann
Mann-Whitney U	$U = 2.3$ or $z = -2.3$, $p = .008$, $r = .5$, $N = 54$ Mann-Whitney U test is a non parametric test (ordinal scaled data, alternative to t-test) used with Z-approximation for $N > 30$, Mann-Whitney U test uses the median for computation.	
Kruskal Wallis test	$\chi^2(df, N = 13) = 23.1$, $p = .007$ Kruskal-Wallis test is a non-parametric test to compare more than 2 groups with each other and is based on the χ^2 test (alternative to ANOVA)	
χ^2	$\chi^2(df, N = 13) = 23.1$, $p = .007$ effect size C_{corr} explores relationship between two or more categorical variables , compares frequencies in a cross-tabulation table. 80% of cells should have expected frequencies of 5 or more.	
t-test	$t(df) = -0.32$, $p = .75$ effect size: η^2 compares the means of independent groups	
paired t-test	$t(df) = -0.32$, $p = .75$ effect size: η^2 compares the means of the same group at different time points	
Bonferroni adjustment	Mann-Whitney U Test as post-hoc test with an adjustment of the alpha level. Bonferroni is a conservative adjustment of the the α level. The α level of .05 is divided by the number of tests that are conducted in a post hoc test, e.g. 3 tests: $\alpha = (0.5/3) = .017$	
one way ANOVA	Analysis of variance is used to compare the mean scores of three or more groups with each other. 'one way' means that there is only one independent variable	
Pearson χ^2	$\chi^2(df, N = 13) = 23.1$, $p = .007$ and Yates' Correction for Continuity (compensation for overestimation) are used if there are only two variables with only two categories, so a 2x2 cross table / contingency table is created.	

Figure A.3: *This figure presents the notation and explanation of the used statistical tests according to Pallant [2010]. The information about the Fisher's exact test is obtained from Ostermann and Wolf-Ostermann [2005] and Pallant [2010].*

Appendix B

Investigating Human Motionings

This section of the appendix contains additional information of the Chapter *Investigating Human Motionings* which were excluded to keep the chapter readable. The following subsections are called as the just as the corresponding sections in the chapter.

B.1 The Frequency of Motionings per Participant

	first	**second**
step_sway	60%	40%
side	71.4%	28.6%
step-back	–	100%

Table B.1: *These are the percentages of cross-tabulation of motioning categories and the characteristic frequency of motionings per participant. In contrast to the table in Section this table presents the percentages across the characteristic and for each motioning category.*

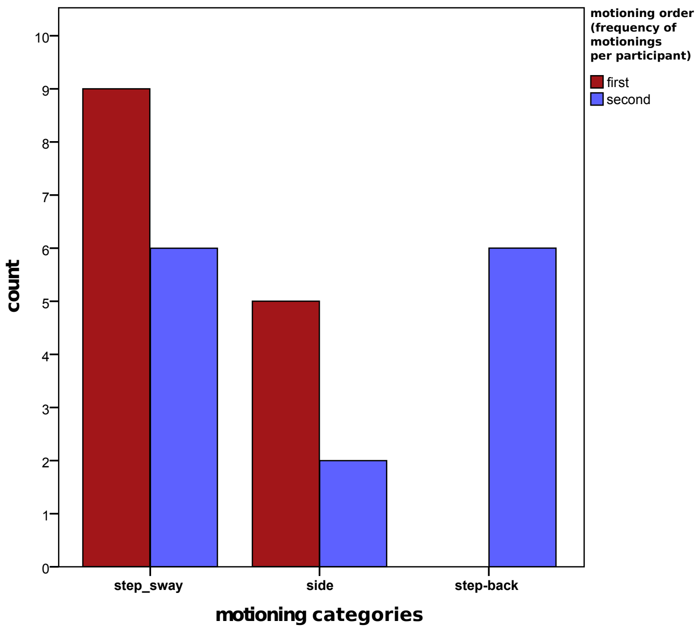

Figure B.1: *This is a diagram of the frequencies of cross-tabulation of motioning categories and the characteristic frequency of motionings per participant. In contrast to the figure in Section this figure presents the percentages across the characteristic and for each motioning category.*

B.2 The Duration of Motionings and Succeeding Pauses

This paragraph was excluded from the Section 6.4.3.

A t-test revealed a tendency for shorter motionings in participants, who motioned only once ($M = 1.16$ *sec.*, $SD = 0.54$ *sec.*), compared to participants, who motioned more than once ($M = 1.54$ *sec.*, $SD = 0.49$ *sec.*) ($t(26) = 1.95$, $p = .06$, $N = 28$). However, this finding is significant when only comparing motionings from the *more blocking* condition. The mean duration of motionings in the condition *more blocking* is significantly longer regarding participants, who motion more than once ($M = 1.8$ *sec.*, $SD = 0.33$ *sec.*), compared to participants, who only motion once ($M = 1.12$ *sec.*, $SD = 0.35$) ($t(13) = 3.68$, $p = .003$, $N = 13$)[1]. The effect size also suggests that this explains the magnitude (55%) of the differences in the mean value $\eta^2 = .55$. However, the limitation and the reason for excluding this paragraph is that the N is very small and the difference between the groups is on average 0.68 sec.

[1] The total sample size (N) is very small because the first motionings of all participants were only considered.

long. Furthermore, the difference in participants, who only motioned once, compared to people, who motioned more than once, might be due to personality traits like patience. Unfortunately, personality traits were not controlled for.

Pauses There are no differences in the duration of succeeding pauses and participants, who motioned more than once and participants, who only motioned once.

B.3 Analysis of the Characteristic Relative Distance

There is no difference in proportion of the values of the *relative distance* ('decrease', 'no change', 'increase') across the *blocking conditions* (Pearson $\chi^2(2, N = 51) = 1.31$, $p = .52$).

B.4 Analysis of the Characteristic Relative Trajectory

The proportion of the *relative trajectory* values for the *blocking conditions* are not significantly different (Fisher's exact test $value = 5.05$, $p = .09$). However, there is a tendency that the value 'past' occurs more frequently in the condition *less blocking* (past: 47.8%, away: 26.1% towards: 26.1%). The value 'towards' occurs more frequently with the condition *more blocking* (towards:57.1%, past: 25%, away:17%). This finding is similar to the findings for the characteristic relative position. If the robot is *more blocking* people would go 'towards' the robot which is also the way out of the room. If the robot is *less blocking* a person would rather go 'past' the robot and also towards the exit.