The Design Space for Robot Appearance and Behaviour for Social Robot Companions

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Abstract

To facilitate necessary task-based interactions and to avoid annoying or upsetting people a domestic robot will have to exhibit appropriate non-verbal social behaviour. Most current robots have the ability to sense and control for the distance of people and objects in their vicinity. An understanding of human robot proxemic and associated non-verbal social behaviour is crucial for humans to accept robots as domestic or servants. Therefore, this thesis addressed the following hypothesis:

> *Attributes of robot appearance, behaviour, task context and situation will affect the distances that people will find comfortable between themselves and a robot..*

Initial exploratory Human-Robot Interaction (HRI) experiments replicated human-human studies into comfortable approach distances with a mechanoid robot in place of one of the human interactors. It was found that most human participants respected the robot's interpersonal space and there were systematic differences for participants' comfortable approach distances to robots with different voice styles. It was proposed that greater initial comfortable approach distances to the robot were due to perceived inconsistencies between the robots overall appearance and voice style.

To investigate these issues further it was necessary to develop HRI experimental set-ups, a novel Video-based HRI (VHRI) trial methodology, trial data collection methods and analytical methodologies. An exploratory VHRI trial then investigated human perceptions and preferences for robot appearance and non-verbal social behaviour. The methodological approach highlighted the holistic and embodied nature of robot appearance and behaviour. Findings indicated that people tend to rate a particular behaviour less favourably when the behaviour is not consistent with the robot's appearance. A live HRI experiment finally confirmed and extended from these previous findings that there were multiple factors which significantly affected participants preferences for robot to human approach distances. There was a significant general tendency for participants to prefer either a tall humanoid robot or a

short mechanoid robot and it was suggested that this may be due to participants internal or demographic factors. Participants' *preferences* for robot height and appearance were both found to have significant effects on their preferences for *live robot* to Human comfortable approach distances, irrespective of the robot type they actually encountered.

The thesis confirms for mechanoid or humanoid robots, results that have previously been found in the domain of human-computer interaction (cf. Reeves & Nass (1996)), that people seem to automatically treat interactive artefacts socially. An original empirical human-robot proxemic framework is proposed in which the experimental findings from the study can be unified in the wider context of human-robot proxemics. This is seen as a necessary first step towards the desired end goal of creating and implementing a working robot proxemic system which can allow the robot to: a) exhibit socially acceptable social spatial behaviour when interacting with humans, b) interpret and gain additional valuable insight into a range of HRI situations from the relative proxemic behaviour of humans in the immediate area. Future work concludes the thesis.

Acknowledgement

For the work which is presented here I am particularly grateful to my supervisors: Prof. Kerstin Dautenhahn who has provided enthusiastic advice, support and guidance at every stage of my studies. Dr. Rene te Boekhorst who has been always ready to help, discuss, and enlighten me with regard to all aspects of statistical analysis. My long suffering colleague, Dr. Kheng Lee Koay, who has been a captive audience for discussing my work as he also works at the next desk as a fellow COGNIRON (COGnitive RObot companiON) project team member! Many thanks to Dr. David Lee who has advised and proof read much of my writing.

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The HRI trials were carried out together by a core team of usually three (or sometimes more) researchers and incorporated many other experiments and aspects of HRI investigations which were not directly relevant to the present study. Beyond the theme of this thesis therefore, I

was not necessarily the prime investigator of many of the particular experiments or HRI trial aspects. There is a problem of attribution in that all of the published papers articles from the study have multiple authors, and from the paper it is not always clear which author is responsible for which part of the work and outcomes presented. In order to clarify the attribution of work and outcomes for this study, the following conventions will be adopted:

> Where work, analysis, findings or conclusions are due solely to me personally, I will adopt first person singular in the descriptive part of the text (e.g "I did this", "I analysed..." etc.). Where my particular findings have been published, I am normally the first author and the citation is of the form Walters et al. (200x). Appendix IV contains hard copies of all the relevant publications where I am the first Author.
>
> Where work, analysis, findings or conclusions are due jointly to myself and one or more others from the research team, first person plural will be used (e.g. "We did this", "We analysed ..." etc.).
>
> Where work was performed by another member, or members of the team, without the authors direct involvement, the team member will be indicated explicitly by their forename(s) and surname (e.g. "Kheng Lee Koay did this", " Kheng Lee Koay analysed ...").

Finally, not least, many thanks go to my family who have allowed me the space to devote so much time over the last few months to writing this thesis during evenings, weekends and at all sorts of strange hours: my love, partner and soul mate Kari, her son Elliot and now our newly arrived daughter, Sophia.

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Chapter 1: Introduction

Robots which are currently commercially available for use in a domestic environment and which have human-like interaction features are often orientated towards toy or entertainment functions. In the future, a robot companion which is to find a more generally useful place within a human orientated domestic environment (e.g. sharing a private home with a person or family) must satisfy two main criteria (cf. Dautenhahn et al. (2005), Syrdal et al. (2006), Woods et al. (2007)):

Technical Capabilities: It must be able to perform a range of useful tasks or functions.

Social Abilities: It must carry out these tasks or functions in a manner that is socially acceptable, comfortable and effective for people it shares the environment with and interacts with.

The technical challenges in getting a robot to perform useful tasks are extremely difficult, and many researchers are currently researching into the technical capabilities that will be required to perform useful functions in a human inhabited environment (E.g. navigation, manipulation, vision, speech, sensing, safety, integration, planning etc.). The second criterion is arguably equally important, because if the robot does not exhibit socially acceptable behaviour, then people may reject the robot if it is annoying, irritating, unsettling or even frightening. Research into social robots is generally contained within the rapidly developing field of Human-Robot Interaction (HRI). Fong et al. (2003) overviews the field of socially interactive robots and provides a taxonomy of design methods and system components.

Goetz et al. (2003) investigated issues of robot appearance, behaviour and task domains and Severinson-Eklundh et al. (2003) documented an HRI trial on the human perspective of a robotic assistant over several weeks. The work of Scopelliti et al. (2005) analysed peoples' views of domestic robots in order to develop an initial design specification for servant robots.

Kanda et al. (2004) present results from a longitudinal HRI trial with a robot as a social partner and peer tutor aiding children learning English. In later chapters of this thesis, more detailed research hypotheses will be formulated and investigated, but all of these studies have two main themes and research questions:

How can a robot behave in a socially acceptable manner?

How can a robot interact effectively with human users?

These questions are different and are not necessarily related. It is possible to conceive of a robot which is very sociable, but not very effective or useful (or vice versa). For example, Kanda et al. (2007) studied a robot which exhibits social cues so that people have the impression that it listens and understands them as they ask for route directions. However, the robot did not comprehend speech, so the human users did not actually gain any useful help from their questions. Breazeal & Scassiallati (1999) presented Kismet, a socially interactive robot head, with a cartoon-like appearance, which exhibits social cues and behaviour in order to gain interaction and attention by humans. This engagement was an end in itself in this case, and there was no direct reward for the human partner beyond entertainment or diversion value.

Investigations which address both these two questions often consider many of the same robot attributes which can be divided loosely into two categories; Robot Appearance and Robot Behaviour:

Ro*bot Appearance:* How a robot is perceived by humans will probably be affected greatly by the robot's appearance. The appearance of a particular robot will depend to some extent on the functionality and technical capabilities of the robot. However, it can also be affected by specific aesthetic and design features, which may change little in terms of functionality but radically affect the external appearance of the robot. Lee & Keisler (2005) have found that humans do indeed form mental models of robots using similar (often limited) information and assumptions to those humans use to form mental models of other humans.

Robot Behaviour: This includes both speech and a wide range of non-verbal behaviours. Khan (1998) identified speech as the most preferred method of commanding and controlling a domestic robot. In the Adaptive Systems Research Group (ASRG) at the University of Hertfordshire (UH), we have provided interactive public demonstrations of robots at the Science Museum, London (cf. the BBC News Website: http://news.bbc.co.uk/2/hi/technology/3962699.stm) and various demonstrations and HRI events at schools and other events with human scaled robots. One question that always occurs is a variation of "can the robot speak to me?". Robot speech is an active area of research, both in the technical robotics and HRI communities, and there is a large body of research that has been published on the more technical aspects (e.g. Haage et al. (2002), Lauria et al. (2002)). In contrast, non-verbal forms of robot behaviour and communication have not been nearly as widely researched. There remains much to discover about how humans perceive and respond to a wide range of non-verbal robot cues and behaviours, including HR proximity, robot appearance, gestures, facial features and expressions, movement styles, speeds, flashing indicator lights, simple beeps and even random mechanical noises due to motors and actuators operating normally.

People's initial impressions of robots will be refined over time, based on perceptions and observations of actual robot behaviours, features, functions and capabilities in order to obtain a closer assessment of a particular robot. Initial assumptions may in fact be very wrong, especially in the case of current robots, mainly due to the limitations of current robot technology. This mismatch between expectations (engendered perhaps by an initially impressive appearance of a particular robot) and the (current) limited technical reality may be the source of the well known effect whereby humans become less interested in interacting with a particular robot after a relatively short time. Kanda et al. (2004) found that in HRI trials with children in regular daily sessions, where a robot acted as a peer tutor to improve their speaking of English, most of the trial participants had markedly reduced their contact with the robot after a period of two weeks. This effect is also noticeable with toy or entertainment robots (e.g. Roboraptor, Robosapiens, Furby etc.). The appearance of these toy robots is specially designed to be interesting and attractive to children. However, once the limited repertoire of the robot has been learned, children will often tire of playing with the robot. In the case of a domestic robot, humans may be more forgiving if the robot is actually carrying out useful work for the household. However, if the robot moves in an unpredictable way, or if humans find the robot's appearance or behaviour unsettling, then they may well react against it and in the worst case, consign the robot to the scrapheap.

One major difference between robots and other domestic machines or objects is that robots move around the home as part of their normal task execution and will necessarily have to interact physically with the human occupants of the house. The robot will effectively be sharing the same living space as the human occupants. Many fundamental social relationships for humans are reflected by, and relate to their use of space (cf. Gillespie & Leffler (1983) & Harrigan et al. (2005)). Therefore, knowing how to control robot proximity to humans will be of crucial importance in how humans will relate to, and co-operate positively with robots in a human orientated domestic environment.

Spatial distances to humans and other objects within the environment are easily and accurately measured by current robot sensors by infra-red laser and sonar scanners under a wide range of conditions and situations. A better understanding of HR proxemic behaviour could potentially allow a domestic robot to regulate, adapt and manipulate many physical aspects of its behaviour to be more socially acceptable and to facilitate interaction with human partners. Human-Robot (HR) proximity is therefore one of the main indicators and measures of human perception of robots used in this study. To understand how humans perceive companion robots I performed exploratory HRI trials investigating their proximity preferences to a robot under a range of contexts and conditions. A main conclusion from these initial exploratory trials was the probable importance of *consistency* of robot appearance and behaviour. This is not a new observation, and other researchers have found evidence that supports the desirability of consistency of robot appearance and behaviour, especially with regard to aiding effective interactions and avoiding undesirable side effects between robots and humans. Furthermore, there is evidence that most people do not actually want a domestic or service robot to be very human-like in appearance, though findings and suggestions for robot behaviour preferences are less conclusive (cf. Khan (1998), Norman (2001) and Dautenhahn et al. (2006)). The present study addressed the following research questions:

1. *Which aspects of robot appearance and non-verbal behaviours are relevant and important to how people perceive domestic service robots?*

2. *What is the importance of consistency between robot appearance and non-verbal behaviours for robots which interact with humans?*

3. *What aspects of robot appearance and non-verbal behaviour are useful for improving the effectiveness of Human-Robot Interactions?*

Implicitly included in these questions is the need for a means of assessing how humans perceive robots and their social abilities, features and behaviours. Ideally this information should be accessible by the robot itself, so that it can modify or adapt its behaviour or appearance to particular humans, contexts and situations as appropriate. The argument for investigating how proxemic sensors mounted on a robot might be used as a means of gaining this information provides the main working hypothesis which guides the work undertaken for this study:

> *Hypothesis: Attributes of robot appearance, behaviour, task context and situation will affect the distances that people will find comfortable between themselves and a robot.*

1.1 Contribution to Knowledge

This study is the first to investigate human robot proxemics in a systematic way, and in more depth than a simple interpretation in terms of social spatial zones along the lines of Hall (1968). The series of exploratory studies which investigated comfortable Human-Robot approach distances are presented in Chapter 3. Many of the original results from these investigations have been published (cf. Walters et al. (2005a), Walters et al. (2007a), Walters et al. (2005b)) or submitted (Walters et al. (2008).

Further investigation of these issues required original developments in HRI social theories, experimental methodology and data analysis. I developed a new video-based experimental

HRI trial methodology, which is described in detail in Woods et al. (2006), Woods et al. (2006a), Walters et al. (2006) and Walters et al. (2007). This video based HRI methodology has now been adopted as one of the main means of evaluating the "user experience" aspects of robot systems developments for the COGNIRON Project European partner institutions. These Video-based HRI (VHRI) methodological developments and both the pilot and the subsequent verification studies and findings are presented in Chapter 4. Initial findings from a VHRI study into peoples perceptions of consistency for robot attributes have been presented in a paper at the 2007 Artificial Life Conference (cf. Walters et al. (2007d)) and is currently in press as a journal article (cf. Walters et al. (2008a). A novel application of an analytical method was applied to assess peoples perceptions for robot consistency of robot appearance and behaviours by quantifying relative ratings of various robot attributes. Details can be found in Chapter 5.

A series of controlled live HRI trials were carried out to confirm and investigate how combinations of various factors, such as robot intention, autonomy, appearance, height, context and situation, affected HR proxemic behaviour,. This is the first time that a controlled study had quantified and measured the relative contributions of a number of individual factors on human perceptions by means of their effects on human-robot proxemic preferences. The relevant results are presented in Chapter 6. and a paper has been submitted for publication based on some of these original findings (cf. Walters et al. (2008a)).

A new empirical framework that unifies the results of my studies is proposed in Chapter 7. This is a necessary first stage towards creating and implementing a working robot proxemic system which can: a) exhibit socially acceptable social spatial behaviour when interacting with humans, b) interpret and gain additional valuable insight into a range of HRI contexts and situation from the relative proxemic behaviour of humans in the immediate area.

1.2 Challenges

The area of research addressed by this thesis is contained mainly within the relatively new field of Human Robot Interaction. By definition, this field is highly interdisciplinary in nature and running a typical HRI trial series involves a multi disciplinary team contributing from many specialised areas including Computer Science, Robotics (both hardware and software systems), Psychology, Statistics, Artificial Intelligence, Engineering and Media. The core team which ran all the HRI trials series had backgrounds in computer science and robotics (Kheng Lee Koay), psychology (Christina Kaouri, Sarah Woods and Dag Sverre Syrdal), and industrial robotics and automation systems (myself).

Running a large scale live HRI trial where people and robots interact and make physical contact with each other involves both technical and organisational challenges. The technical challenges are to develop robot systems which are able to provide specified controlled appearance, behaviour and performance in a safe and robust manner along with the associated development of measuring, data collection and processing systems. However, in addition to these purely technical challenges, there were also organisational, methodological, ethical and safety challenges that had to be overcome. All of the team involved in the large scale HRI trials have had to develop new techniques and skills, both within and outside their existing areas of expertise. Walters et al. (2005) provides an introduction to running large scale live HRI trials, and I discuss and provide practical solutions which have been found useful in addressing the issues raised. Some of the issues raised during the course of HRI trials run for this study are discussed in Chapter 8.

1.3 Personal Learning Outcomes from the Study

The challenges I have addressed personally, and which are relevant to this study, have been many and have required me to developed new skills, knowledge and capabilities. As the team member with industrial experience in manufacturing, robotics, mechatronics, control and automation, I was generally responsible for the robot hardware developments and much of the associated software development. This has enabled me to apply and extend my previous experience to mobile robots that must interact reliably and safely with humans. In addition to allowing me the opportunity to increase my technical knowledge and skills in designing and building various add-ons and creating programs for the standard PeopleBots™ used for all the HRI trials, it has also required that I become familiar with the often complex requirements from the ethical concerns, safety and risk management of running trials which involve people. More details of the robot hardware and software developments can be found in Chapter 5 and in Appendices I and II. For details of risk management, health and safety and ethical issues see Chapter 2.4

The necessarily human-centred perspective of HRI trials is gained largely by using various qualitative and quantitative techniques and methodologies based on those from the fields of psychology and statistical analysis. The development of questionnaires and the associated techniques of structured interviews are a main means of collecting data from HRI trials, and I have gained experience in developing and utilising both methods in order to obtain participants views during and after HRI trials. I have also developed the necessary specialised mathematical and statistical skills and knowledge in order to apply appropriate analytical techniques to quantitative results obtained from this human centred HRI trial data.

In order to provide a record of HRI trials, I have been responsible for video recording HRI trial sessions and I have developed my abilities to record and edit video media. I have also learned many of the techniques for post analysis of video recordings of trial session, such as coding and annotating techniques and other methods for further statistical analysis. In addition, I have been responsible for building the electronic and wireless hardware, which performs automatic annotation of the video record directly by participants by means of a small wireless hand held signalling device. I was responsible for the idea of using video based HRI trials, and as a result I have further learned how to direct, create, edit and produce videos of controlled HRI scenarios that are suitable for use in video based HRI trial experiments.

1.4 Acronyms, Glossary and Definitions

This section contains some important definitions and notes which are important for understanding terms used in this text and defining the scope of the study. Table 1 contains acronyms, definitions and descriptions of specialised words used in the text.

Table 1: Acronyms and Descriptions

HR	Human-Robot or Human to Robot, depends on context.
RH	Robot to Human.
RH Approach Distance	Robot to Human (comfortable) Approach Distance
HR Approach Distance	Human to Robot (comfortable) Approach Distance
HRI	Human Robot Interaction
HRI Trial	Human Robot Interaction Trial
VHRI Trial	Video-based HRI Trial - HRI trial conducted using videos of robot and humans interacting, rather than live robots.
HCI	Human Computer Interaction
UI	User Interface
GUI	Graphic User Interface
CLD	Comfort Level Device - used to provide participant feedback in HRI trials.
VE	Virtual Environment
IVE	Immersive Virtual Environment
WoZ	Wizard of Oz - A method by which unseen operators control robots in HRI trials..
Robot House	A specially fitted out apartment which provides a more natural non-lab environment for HRI experiments.
UH, ASRG	University of Hertfordshire, Adaptive Systems Research Group
COGNIRON	COgnitive RObot companiON

1.4.1 Human-Robot Interaction: Situation and Context

In this thesis, the external physical factors of an interaction are referred to as the *Situation of an HRI* (or normally just *Situation).* The term *Situation* denotes the physical environment where the interaction takes place, including the physical shape and size of the immediate area, the location, size and orientation of obstacles, and the location, posture, orientation and position of humans (e.g. standing, seated, behind desk, against wall etc.) within the immediate area.

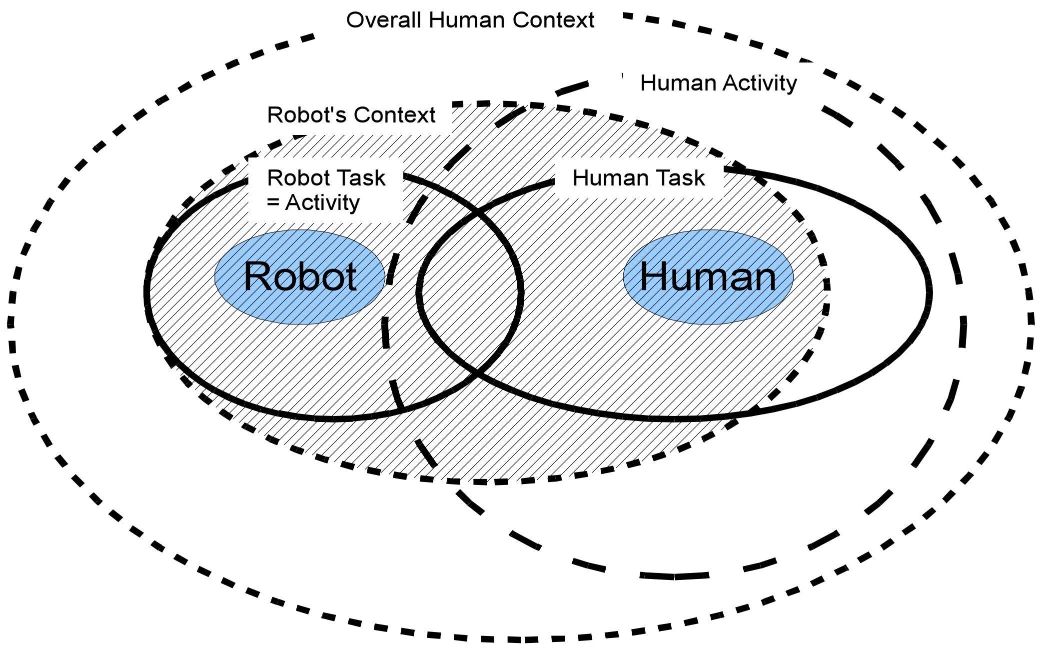


Figure 1: The robot's perception of human contexts, tasks and activities (shaded) will always be limited.

The purpose and intention of a Human-Robot Interaction (HRI) are separately defined here as the *Context of an HRI* or more simply C*ontext*. The *Context of an HRI* is further limited for the purposes of this study to the *Robot Context*. In general, whenever the *context* of an interaction between a human and a robot is referred to in this text, this should be taken as referring to the r*obot context of an HRI*. The robot context normally refers to the current context, which in this study is normally the task which the robot is currently carrying out (e.g. fetching, carrying, navigating, verbal communication, physical interaction etc.). In this thesis, the term *scenario* is used to encompass both the context and situation of a HRI.

Note: Figure 1 illustrates how the robot's view of a particular context will always be limited by what is accessible to its sensors and perceptual abilities. Some aspects of individual Human activities and tasks will always be outside of the robots perceptual abilities either due to technological limitations, or specifically by design choices, limitations and human preferences. Therefore only a limited perception of the overall (human centred) context will be apparent to the robot at any time. Humans may either be performing a task, or any number of non-task based or other activities. Many aspects of these are not accessible or even perceived by the robot. For a domestic or servant robot there is no real distinction between an activity and a task, as (currently) servant robots only undertake activities in order to accomplish tasks. Therefore each robot activity can be considered to be a (sub-)task.

1.4.2 Robot Types

In this thesis, the terms Mechanoid, Humanoid and Android are used to describe robots with particular appearance features. The definitions of Mechanoid and Humanoid robots used here are based on the definitions for animated agents adopted by Gong & Nass (2007) and for Android robots from MacDorman & Ishiguro (2006):

Mechanoid - a robot which is relatively machine-like in appearance. In both live and video based HRI trials described in this thesis, a robot described as mechanoid will have no overtly human-like features.

Humanoid - a robot which does not have a realistic human-like appearance and is readily perceived as a robot by human interactants. However, it will possess some human-like features, which are usually stylised, simplified or cartoon-like versions of the human equivalents, including some or all of the following: a head, facial features, eyes, ears, eyebrows, arms, hands, legs. It may have wheels for locomotion or use legs for walking.

Android - a robot which exhibits appearance (and behaviour) which is as close to a real human appearance as technically possible. The eventual aim is to create a robot which is perceived as fully human by humans, though the best that can be achieved currently is for a few seconds under carefully staged circumstances. The main scientific purpose of current android robots is usually to investigate interaction and social aspects of human cognition, rather than for use as domestic or servant robots (cf. Ishiguro (2005)).

1.5 Overview of Thesis Content

This chapter has introduced the broad subject areas of interest to this thesis and highlighted the significant research questions, working hypotheses which are addressed in the following chapters. The original contributions to knowledge from the study are listed and my personal learning outcomes are summarised. A number of working definitions are provided for specific terms and concepts important for a full understanding of the following Chapters of the thesis.

Chapter 2 provides a review of relevant literature which first considers human-human proxemics, then comparable and relevant findings from the fields of both Human Computer Interaction (HCI) and Human-Robot Interaction (HRI) research. The problem of robot appearance rating and assessment is then discussed. The focus of the present study is placed into context within the wider area of existing and parallel HRI research concerning consistency of robot appearance and behaviour.

Chapter 3 presents the initial exploratory experimental part of this study, which concentrated on exploratory investigations into Human-Robot (HR) comfortable approach distances. Experimental methodology and technology development, and exploratory experiments investigating human perceptions of robot movements are the main subjects of Chapter 4. A video based HRI experiment looking at consistency in robot appearance and behaviour is presented in Chapter 5. Chapter 6 presents a series of controlled experiments which examined multiple combinations of factors and conditions including robot appearance, behaviour, situation and context. Table 2 shows the relationship between the various main COGNIRON HRI Trial Series and the individual experiments relevant to this thesis which are presented in Chapters 3 to 6 of this thesis.

Table 2: Experiments Performed for this Study

COGNIRON Main HRI Trial (HRIT) Series	Relevant HRI Experiments	Acronym	Chapter
VICTEC HRI Trials series with child Groups. Interactive games with a Robot. 2004	Initial Proximity Experiment (IPE): HR approach distances and orientations with child groups relative to robot.	IPE	3.2
HRI Trial series with individual humans and a robot in a shared workspace. 2004	Comfortable Approach Distance Experiment (CADE): HR and RH proximity trials with adults and a robot..	CADE	3.3
Demonstration HRI trials run for the AISB Symposium at UH. 2005	Robot Voice Approach Experiment (RVAE): Comfortable approach distances to a robot with different voices.	RVAE	3.4
Robot to Human Approach Directions: Pilot HRI Trials. 2005	Pilot Study (PS) for Video-based HRI (VHRI) trials: Exploratory Investigation into novel trial methodology	PS VHRI	4.1
Robot to Human Approach Directions: Main HRI Trials. 2005	Main Study (MS) for VHRI methodology: Verification of the novel VHRI trial methodology	MS VHRI	4.2
Video based HRI trial into humans preferences and perceptions of robots. 2005	Robot Appearance and Behaviour Experiment (RABE): Exploratory VHRI trial investigation of human perceptions of consistency of robot attributes.	RABE	5.2
Longitudinal live HRI trials into human perceptions, preferences and habituation for domestic service robots.	Live Multiple Factor Experiment (LMFE): HRI trial investigating HR proxemics, preferences and perceptions of robot appearance and behaviour.	LMFE	6

Chapter 7 proposes an empirical framework for HR proximity, appearance and other non-verbal factors, which allows a number of provisional hypotheses to be made. The thesis findings and outcomes are discussed and reviewed in Chapter 8. Finally, Chapter 9 concludes and provides a roadmap for further research work in the area and a number of open questions are identified. Suggestions for future work are made with regard to verifying, adapting and extending the HRI empirical proxemic framework, suitable for implementation as a robot proxemic system.

At the end of Chapters 3 to 6 which primarily present experimental results, analysis and findings, a short final sub-section summarises my particular responsibilities for the work, analysis, findings, conclusions and outcomes contained within. For the other Chapters 1, 2, 7 8 and 9, the work, discussions and arguments presented are my own.

Chapter 2: Human Perceptions of Social Robots

A domestic service robot will move around the areas in which people live and therefore will have a physical embodiment that is qualitatively different from that of a computer or most other domestic appliances. As the robot carries out tasks, it will have to negotiate its way through encounters with the human inhabitants by exhibiting acceptable verbal and non-verbal social behaviour, without making them feel uncomfortable or annoyed in what is their home territory. The literature review presented in this Chapter focusses on those non-verbal attributes and factors which are likely to affect humans' perceptions and preferences for the social acceptability of domestic and service robots. Embodied non-verbal interactions, such as approach, touch, and avoidance behaviours, are fundamental to regulating human-human social interactions and this has provided a guide for more recent research into human reactions to robots. The general term for the study into how humans use and manipulate distances between each other with regard to social behaviour and perceptions is called *proxemics*. Harrigan et al. (2005) provide a good general introduction and reference for research into non-verbal human behaviour, including proxemics. Factors affecting how humans may relate to and perceive social robots include attributes affecting both robot appearance and behaviour. In this chapter a literature-based review of relevant research is presented. The structure of the chapter is as follows:

> *Section 2.1* - Reviews relevant findings from the field of human-human proxemics, with a view to inspiring the generation of initial working hypotheses for testing in equivalent human-robot proxemics contexts and situations in HRI trials. Investigation of human-robot proxemics forms a major part of the initial exploratory investigations for this thesis and findings from the HRI trials are presented in Chapter 3.

Section 2.2 - As robots find real uses in a domestic environment, the question of how human will perceive and relate socially to these robots is important. Over the last few decades, there has been a large body of research investigating how people respond to, interact with, and perceive the social aspects of computers and computer-based technology. Thus includes computer software application interfaces and also the closely related areas of computer-animated agents, virtual environments and video games. Relevant existing research and findings from the field of Human Computer Interaction (HCI) are reviewed in this section.

Section 2.3 - The focus of this study is on how people view robots, with the eventual aim of informing robot designers how they can achieve acceptable and desirable robot appearance and behaviour. The emphasis is therefore on how humans perceive and respond socially to robots. This section contains a review of applicable research findings from the relatively new research field of HRI, and includes subsections on robot proxemics, appearance, non-verbal aspects of speech and consistency of robot appearance and behaviour.

Section 2.4 - In order to measure, assess and test hypotheses in the field of HRI, it is usual to set up experiments which involve people interacting with robots in controlled HRI trials. HRI trials are often complex, and multi-disciplinary in nature, so this section provides an overview of HRI trial methodology and related topics.

Section 2.5 - This section summarises and discusses the disparate findings of the earlier sections as a coherent body of evidence. Some common issues, outcomes and themes are identified which are used to direct and plan the further progress of the current study.

Section 2.6 - Chapter Summary and Conclusions

2.1 Human Social Spaces and Proxemics

Research into social and personal spaces and distances between humans is called Proxemics. Hall (1966) observed that human social spatial distances varies by the degree of familiarity between interacting humans and the number of interactors. Where interactions took place between individual humans, who were familiar with each other and in a private situation, the distances taken relative to each other by the interactors tended to be smaller, and where the encounter was in a more public situation, with larger groups or less familiar individuals, the distances taken between interactors tended to be larger. Later, Hall (1968) provided a theoretical framework which identified four main distance ranges which categorised the main social spatial zones by interaction situation (Table 3).

Table 3: Human-Human Personal Space Zones (cf. Lambert (2004))

Range	Situation	Personal Space Zone
0 to 0.15m	Lover or close friend touching	Intimate Zone
0.15m to 0.45m	Lover or close friend only	Close Intimate Zone
0.45m to 1.2m	Conversation between friends	Personal Zone
1.2m to 3.6m	Conversation to non-friends	Social Zone
3.6m +	Public speech making	Public Zone

Hall's original social spatial zone distances were estimated visually in terms of arm lengths, close contact and threat/flight distances, but more recently have been assigned estimated numerical measurement ranges by researchers. Later work in psychology has demonstrated that social spaces substantially reflect and influence social relationships and the attitudes of people (cf. Gillespie & Leffler (1983)) and has addressed some of the shortcomings in Hall's original work, which only related to broad categories of interpersonal distances. Further studies have modified the predictions of Hall's original broad social spatial zone model (which was mainly based on observed cultural differences) and have identified other factors which affect human-human proximity. In early proxemic trials, which used a hat-stand as a control, Horowitz et al. (1964) found that participants were “comfortable” approaching arbitrarily close to inanimate objects. Sommer (1969) stated that there were no social proxemic effects for objects and that people can approach arbitrarily close to inanimate objects without any discomfort or problem.

Further tests by Stratton et al. (1973), in a study on comfortable human-human approach distances, found that typical mean "comfortable" approach distances between human participants were approximately 51cm (20in). This study also found that there were significant differences in approach distance that correlated with the participants notion of “self-concept”. Participants who rated highly in self-concept approached the experimenter significantly closer then those who rated low in self-concept. Self-concept was effectively used as a relative measure of the (social) status of participants. This study also found that participants approached a dressed and headless tailor's dummy to a mean approach distance of 55cm (22in). This was slightly (but not significantly) greater than the mean approach distance for the human-human cases. The authors suggested that the participants may have taken a slightly greater approach distance due to a mild form of the “fear of the strange” effect as observed in animals and noted by Hebb (1958), where chimpanzees were observed to keep greater distances from images of distorted chimpanzee faces and limbs than they did to non-distorted parts or other images. A similar effect has also been noted with regard to dogs and robots; Kubinyi et al. (2004) have found that adult dogs tend to leave larger distances between themselves and a “furry robot” dog than for either a toy car (the control), a real puppy or a “hard robot” dog. This is possibly related to the animal equivalent of the “uncanny valley” effect in humans noted by Mori (1970) and is discussed further in Section 2.3

Burgoon & Jones (1976) in their review of proxemic research, categorise the factors which affect human proximity as external or *Environmental* factors of an encounter (location, crowded, boundaries, territory, etc.), internal or *Interactant* factors (status, age, friendship, gender, etc.) and the N*ature of the interaction.* This last category includes the purpose, intention and state (e.g. ignoring, talking, passing, angry, happy etc.) of those interacting, and also includes manipulations of the proxemic distance to accomplish subtle aims (dominate, reward, punish, ingratiate, etc.).

Gillespie & Leffler (1983) have reviewed many of the published studies into human-human proxemics and have concluded that most of the observed variation in social distances between *communicating* humans can be accounted for by the relative status of the interactants. In general, the higher the relative status of one of the people in an interaction, the more distance other relatively low status individuals will keep from them. One the other hand, relatively high status individuals will not respect the social spaces of other lower status individuals to the same degree. They provide an example to illustrate these ideas: A senior doctor (relatively high status) will approach junior staff closely and may even touch or physically guide a junior doctor, nurse or patient to indicate or reinforce what they are saying. On the other hand, a subordinate would not dream of approaching the senior doctor so closely and definitely would not touch them! This is an extreme situation, but the basic concept holds for any interacting group of people. The concept of status is not a one dimensional quantity: It can be perceived in terms of a combination of factors including age, hierarchical seniority, intelligence, charisma, physical presence, gender and force of personality. The concept of status provides a possible explanation why people generally become closer friends with others who have relatively similar status as they tend to adopt similar social distances towards each other. This tends to make them feel relaxed and comfortable in each other's presence. Where an interaction is between individuals of different status, there is a disparity in the social distances they take towards each other and therefore less comfort in interactions with each other.

Another factor which can also affect proxemic distances is perceived threat. This is possibly related to the "flight reaction" originally observed in birds and reported by Hediger (1961). This occurs when a perceived threat rises beyond a certain level and the animal will prepare to either fight or flee according to its nature and the context of the threat. Humans and primates adopt a response which is proportional to the magnitude of the perceived threat. Where the threat is immediate and real, they will exhibit a classic "fight or flight" reaction, in common with most other animals. In slightly uncertain situations, where the perceived threat is actually minimal (i.e. feeling uncertain rather than threatened), they will take up slightly greater distances from the source of the perceived potential "threat".

Another factor which may affect the relative distances between communicating humans may be the result of relatively small manipulations of the distance between interactants. This has been proposed as a social "reward and punishment" mechanism whereby humans can communicate subtle messages (often unconsciously). This was proposed by Burgoon & Jones (1976) as a part of a theory to explain many (seemingly contradictory) aspects of human-human proxemic behaviour. They proposed that in any interaction between humans, there would be an optimal social distance that would be in place for each interactor. One or other of the interactors could "punish" or "reward" the other interactor by making (usually relatively small) adjustments in the appropriate direction. For example, where a man is interacting with a woman, if she wanted to encourage his attention she may "reward" him by moving closer than might be expected. On the other hand if she wanted to discourage him, she would literally "keep her distance". The same theory can also explain how high status interactors can "reward" lower status interactors by moving closer, but lower status interactors can "reward" higher status interactors by keeping a greater distance. The theory does produce hypotheses which can be tested with regard to human-robot proxemic situations.

2.1.1 Measurement of Human-Human Interpersonal Distances

There is a practical issue of obtaining accurate and comparable measurements for the distances between humans, and this may provide lessons for measuring distances between humans and robots. In human-human proxemic studies, including those presented above, a number of systems for measuring interpersonal distances have been used including; face to face distance, chest to chest distance, or distance between nearest body parts. In human proxemic experiments, commonly carpet tiles or floor grid markings have also been used to estimate interactors positions, and this would provide a distance measured between respective "centre of areas" of interacting people. Most research papers do not provide full details of how the measurements were made, and it has been noted by Harrigan et al. (2005) that many human proxemic experimenters have simply estimated their experimentally obtained distances by direct observation, or by recording markings on scale diagrams. In many cases, the experiment was performed by asking a participant to imagine or envisage an experimental situation, and then estimate the distance or make a mark on a scale diagram themselves.

Clearly, this is a problem for human proxemic studies in that it is difficult to directly compare quantitative findings from different research findings. In practical terms this would imply a possible difference of the order of 20cm or more between measurements of the same distance for different methods. This is possibly not important for longer range interactions over distances comparable to Hall's social and public spatial zones, but for human-human interpersonal distances, this review has provided evidence that even relatively small differences and changes in human proxemic distances of the order of 2 cm to 15 cm, can be significant (cf. Horowitz et al. (1964), Sommer (1969) & Stratton et al. (1973)). This problem is addressed with regard to HR proxemic measurements in 2.5.2

2.2 Computers and Social Interaction

Some fundamental insights with regard to interfaces between computers and users have already been found for the closely associated field of Human-Computer Interaction (HCI) and may well have relevance for HRI. Nass et al. (1994) and Reeves & Nass (1996) have provided conclusive evidence that, when interacting with computer technology, people exhibit many aspects of social behaviour towards computers. They have shown that people have a social relationship with computers, treating them as social entities in many ways, including politeness, reciprocity and attribution of gender stereotypes and personality in spite of knowing very well that computers are machines. Most current robots basically consist of a mobile platform which contains a computer to interpret data from sensors and control the robot's manipulators and actuators. A large part of the control system of a typical robot will therefore be based on computing technology of some kind. Therefore, in common with computers and other technological artefacts, it can be expected that domestic robots will be treated in a social way by the human inhabitants of their working environment. However, the physical embodiment, movements and presence, and interactivity of a robot in the environment are very different from that of stationary computers and other technological artefacts. It is expected therefore that people may react and relate socially to robots in some of the ways that they do to computers and other artefacts, but there will certainly also be differences. Some of the non-verbal human-like attributes of computers, computer generated agents and speech which are common to both robots and computers are discussed below.

Immersive Virtual Environments (IVEs) provide a sense of physical embodiment with agents, and this may also have relevance to how people perceive and react to robots.

2.2.1 Non-Verbal Aspects of Speech in HCI

Computer generated speech and speech recognition have been used in applications for many years since the 1970s, and with the development of reliable commercially available speech recognition systems since the 1990s, they are widely used in a number of applications. There is now a large body of research into the technical aspects of both computer based speech recognition and speech synthesis (see Kirriemuir (2003) & Everett et al. (1999) for a review of common computer speech applications). However, it is only in recent years that the quality of speech synthesis systems is becoming good enough to provide a working range of reasonably high quality synthesized voice styles which are suitable for research into user performance and preferences.

Nass & Moon (2000) originally performed a series of studies into the reasons why people relate socially to computers, with interactions made by standard keyboards and text displays as control conditions, and male and female voices with talking head type displays. Their main conclusion was that humans "mindlessly" apply social rules and considerations when appropriate (social) cues are encountered. Their findings suggested that simplified imperfect implementations of human attributes may elicit nearly as many social responses as a "perfect implementation" and they suggest that possibly a "lack of verisimilitude increases the saliency of the computer's non-humanness" (i.e. a non-perfect implementation of human-like behaviour is consistent with the non-human-like computer appearance and thus seems more believable). From their studies they also found evidence to suggest that computer speech is a major factor that affects how people perceive and relate to a computer socially.

More recently, researchers have investigated aspects of human perceptions, preferences and responses to computers with speech systems relating mainly to information terminals, websites and telephone answering services. Dahlback et al. (2007) has studied the effects and preferences of users for a (website-based) disembodied speech communication application with different accents on users responses and preferences. Users' overall tended to prefer accents which were similar to their own. They also found similar accented agents more knowledgeable, in spite of evidence that differently accented agents may be actually be the most knowledgeable. This does raise a question as to users perceived trustworthiness of agents with a different accent than their own.

Many recent studies have been performed which involved computer speech in conjunction with computer-generated graphic displays featuring whole body animated agents, or with virtual (computer animated) agents in virtual environments (VEs). Modern graphically capable desktop personal computers are powerful enough to animate and display relatively sophisticated computer generated characters, and these have been used to provide a visual representation of an animated agent on the screen alongside, or as part of, the application software display. Animated agents are essentially computer programs that aid users with tasks carried out at the computer. They often include a speech-based interface and can act intelligently and autonomously on behalf of the user. The agent animations may be based on real video, cartoon-style graphics or model-based 3-Dimensional (3D) graphic representations. Users relate socially to computers whether an animated agent is used or not, but an animated agent will affect the form and degree of the (human-computer) social relationship and there have been many comparison studies which may inform the current investigation of how humans will relate socially to robots. In a review of animated agents, Dehn & van Mulkin (2000) have identified arguments both for and against the use of animated agents. Briefly, both advocates and those who oppose the use of animated agents assume that an animated agent will render the system more human-like, but argue that this may confer benefits or problems respectively. These arguments are outlined here under two categories and their possible applicability to domestic robots is assessed:

User Motivation and Enjoyment - Advocates assume that the use of an animated agent will make the process of using the system more engaging, interesting and enjoyable, and thus motivate users. Others argue that the agent will be a distraction and may hamper user performance or even be an annoyance (e.g. the Microsoft Office animated helper agent system "Clippy", cf. Livingstone & Charles (2004)). These attributes can be grouped broadly under the category of *User Preferences*. Clearly, a robot has a physical presence that cannot be turned on or off, as is the case for an animated agent. However, findings from HCI with regard to users' preferences for the appearance and behaviour of animated agents in applications where they have been beneficial may provide insights into likely or possible preferences for robot appearance and behaviour.

Task Performance and Effectiveness of Interaction - Advocates assume this will take advantage of peoples' existing interaction skills and thus enhance the interaction with the computer. Those opposing say that users may gain a false mental model of the system, assume capabilities that it does not possess and therefore be disappointed when the system does not perform to expectations. The persona and appearance of the animated agent may facilitate the interaction with the system by providing social cues and feedback in a non-verbal way. Dehn & van Mulkin (2000) recommended that the degree and style of anthropomorphism of the agent animation should be tailored to both the user and the actual application. For example, a sympathetic, friendly animated character may elicit more personal responses from a user than would a more business-like brusque character. This would be good for a health questionnaire or diagnostic program for example. Users may also prefer it for a range of other applications but it may be well counter-effective for certain programs (e.g. financial or maths) as it may tend to elicit irrelevant answers or be distracting.

Dryer (1999) tested people's dispositions to perceive anthropomorphic computer software agents as having a personality, even when none was intended. Though this study was conducted using software agents, many of the conclusions may equally apply to the perception of robot personality. Dryer found that participants rated the software agents primarily along four dimensions. Two dimensions were related to perceived personality: cooperative versus competitive and outgoing versus withdrawn. Two dimensions were related to the agent's appearance and behaviour: sophisticated versus “cartoon-like” and human versus animal.

McBreen & Jack (2001) evaluated a range of animated agents, with regard to gender and realism of appearance in an E-Retail application which advised potential customers on room decoration and furnishing. Results showed that participants expected a high level of realistic human-like verbal and consistently high non-verbal communicative behaviour from human-like agents. Participants overall had a preference for 3D rather than 2D cartoon-like agents and desired to interact with fully embodied animated agents, as opposed to disembodied voices or talking-head agents. Their findings also indicated that the agent's gender had a main effect on people's perception of the agents. Both disembodied and full-bodied agents were generally perceived as more polite and female voices as less annoying, but more competent and helpful. Overall ratings of the agents showed no significant application dependency.

Paiva et al. (2004) developed a computer-based, animated system which allowed school children to enact virtual 3D scenarios which addressed the problem of bullying in schools. Their system allowed children to witness bullying situations (from a third-person perspective), using role playing and empathic synthetic characters in a 3D environment. In order to achieve believability (and in particular, empathy) with the animated characters in their system they consider the characters' embodiment, emotional expression, proximity with the user and the (form of the) emotionally charged situation to be important components of the children's experience. Significant effects were found for gender, with most children (both boys and girls) empathising with the male child victim. With regard to empathy, 86% of children felt sorry for one or more of the characters (typically the victim) and 72% felt angry towards one or more of the characters (typically the bully) indicating that the cartoon-like animated agents generated appropriate empathic responses in child users. However, adults rating the system did not exhibit an empathic relationship with the agents, but rather used factors such as the physical appearance of the agents were used to rate the system.

More generally Bengtsson et al. (1999) found in experiments that participants rated anthropomorphic computer interfaces as more positive, credible and understanding, but the least anthropomorphic computers were actually found to be most influential in a decision-making task. It seems that more anthropomorphic animated interfaces may be perceived as being more subjective. The authors highlight issues of trust, authenticity and credibility with regard to data presentation by computers. Nass & Lee (2001) in an experiment examining participants' preferences for animated agent's behaviour and appearance, found that when an agent's personality and the verbal message tone being communicated were consistent, it was evaluated more positively by participants. A later study by Gong & Nass (2007) examined consistency preferences for animated computer agents with talking faces and concluded that a preference for consistency appears to be a strong human propensity. Inconsistency between verbal behaviour and non-verbal behaviour is seen to be an indicator of deception, and therefore will contribute to a lack of trust. In experiments to test their conclusions, they found that very human-like appearance paired with a simulated human (synthesized) voice in particular was perceived by participants as inconsistent. The teaming of a humanoid (less human-like) appearance and human voice was still perceived as inconsistent, but more acceptable. Overall, the more human-like voice was preferred for its superior quality and understandability for longer speeches, even for the humanoid talking head.

2.2.2 Virtual Environments

Bailenson et al. (2003) have investigated issues of interpersonal distances in virtual environments. The controlled variables were participant gender, virtual human gender, virtual human gaze behaviour, and whether the virtual humans were allegedly controlled by humans (avatars) or computers (agents). Overall, participants maintained interpersonal distances that were comparable to those for real humans (approximately 0.5m), keeping greater distances from virtual humans when approaching their fronts compared to their backs. When passing or approaching virtual humans, participants tended to give more personal space to virtual humans who engaged them in mutual gazes. However, when virtual humans approached them and invaded their personal space, participants tended to move farthest from computer-controlled virtual human agents. However, when participants *believed* that virtual humans were avatars (even when really computer-controlled) they also tended to keep further interpersonal distances than when they believed the agents were computer controlled. The significant differences between interpersonal distances found by this study were of the order of 3 to 7 cm (approx. 1.4 to 2.8 inches). Another interesting finding was that questionnaire derived participant ratings of social presence did not predict interpersonal distance. They proposed that this is due to the difficulty in self-reporting the "attribution of sentience" to an animated agent and suggested that "interpersonal distance may be a better measure of social influence".

Garau et al. (2003) found that for aspects of appearance and behaviour of avatars (virtual environment representations of other people) in an IVE, the fidelity of an avatar must be accompanied by consistent realistic behaviour in order to enhance participants communication experience. Low fidelity appearance, if accompanied by realistic (human-like) gaze behaviour actually gained a negative rating on a number of measures by participants. Correspondingly, higher fidelity avatar appearance must be accompanied by the more realistic gaze behaviour to gain a positive rating. More recently, Bailenson et al. (2005) have conducted further studies which examined how participant assessments of social presence in an IVE are influenced by variations in how much an embodied agent resembles a human being in both appearance and behaviour. Findings indicated that (social) presence rating by participants was lowest when there was a large mismatch between the appearance and behavioural realism of a virtual agent.

Figure 2: A scene from an "Interactive Psycho-Drama" played in an Immersive Virtual Reality Environment (cf. Anstey et al. (2004))

Others are extending the application boundaries of IVEs and exploring new ways for animated agents to influence and interact with humans in virtual spaces. For example, Anstey et al. (2004) are using IVEs to develop "Virtual Psycho-Dramas", which are semi-scripted, interactive plays which allow the human interactor to influence and be influenced by interacting with animated agent actors as the drama unfolds (see Figure 2). The dramas use artificial intelligence techniques for the creation of responsive, believable, intelligent agents that act as characters in the story. The psycho-dramas can be used to investigate and explore ways in which people can be affected by the agent's behaviours and actions. The appearance of the agent actors is cartoon-like, but conceivably could be adjusted or changed as desired.

Another medium which can be considered to be similar to an IVE, is that of video games and on-line Multi-User-Dungeon (MUD) type game worlds (such as World of Warcraft, Second Life etc.). There is little research on these relatively new applications of virtual environments which explicitly refers to domestic robot companions. However, it is possible to conceive of a Science Fiction type virtual world where robots (realised as animated agents) are commonplace. This would be an ideal way to test and trial experience of HRI robots, appearances, behaviours (and even control software and technology) with large samples of people.

2.3 Robots and Non-Verbal Social Interaction

Within domestic environments, most current robots have mainly been seen as toys with (often limited) entertainment functions. These robots have usually exhibited a relatively small number of interaction functions and have often outworn their welcome after a relatively short time. In recent years the development of robots' technical capabilities has enabled them to perform some useful functions such as simple cleaning tasks (e.g. the ROOMBA vacuum cleaning robot, Figure 3), lawn mowing and basic (remote) security monitoring. However, these limited tasks have been selected for initial domestic robot applications specifically because they actually require little in the way of human interaction. If robots are to become truly useful in a human centred domestic environment, in addition to performing useful tasks, they must also be socially acceptable and effective when interacting with people they share their working environment with (cf. Dautenhahn et al. (2005), Woods et al. (2007) & Syrdal et al. (2007)).

Figure 3: The Roomba vacuum cleaning robot, iRobot Inc.

Investigating non-verbal social aspects of domestic and service robots provides the focus of the work for this study and also for the review of relevant research presented in this section. An excellent overview of socially interactive robots (robots designed to interact with humans in a social way) is provided in Fong et al. (2003) and though the research is now becoming slightly dated, many of the robot systems described are still being used for original HRI research. Although speech content and dialogue is an important part of these interactions, and many Human-Robot Interactions (HRIs) necessarily involve speech, the main emphasis of the research reviewed in this section is on the physical, spatial, visual and audible non-verbal social aspects of robots which interact socially with humans. Bartneck & Forlizzi (2004a) propose the following definition of a social robot:

> *"A social robot is an autonomous or semi-autonomous robot that interacts and communicates with humans by following the behavioural norms expected by the people with whom the robot is intended to interact" Bartneck & Forlizzi (2004a), p. 593.*

This definition does not say what would actually be humans' normal expectations with regard to socially interactive robots! Fong et al. (2003) provide some indications by describing socially interactive robot characteristics: A socially interactive robot may express and/or perceive emotions, communicate with high-level dialogue, learn and/or recognize models of other agents, establish and maintain social relationships, use natural cues (gaze, gestures, etc.), exhibit distinctive personality and character, and learn or develop social competencies. In the light of these attributes the following general assumptions for social robots can also usefully be made:

If a robot was fully human-like in appearance and behaviour, it would be reasonable to assume that other humans would respond to it socially as they would to another human and expect it to behave like a human. It would also be reasonable to assume if the robot looked and behaved exactly the same as an animal (e.g. a dog or cat) then humans would respond to it as they would to a pet. At the other extreme, Reeves & Nass (1996) have shown that people do respond socially to technological artefacts in many of the same ways that they do other humans. However, as long as robots can be distinguished from biological organisms, which may be the case for a long time to come, it is unlikely that people will react socially to robots in exactly the same ways that they might react both to other humans or other living creatures in comparable contexts.

Norman (2001) draws inspiration for how robots should interact with humans from a number of sources: Human-Computer Interaction (HCI), automation, science fiction (e.g., Asimov's 4 laws of Robotics, Asimov (1950)), computer-supported cooperative work and human attributes including consciousness, emotion and personality. He argues for a robot that would be a cooperative team member rather than an autonomous, independent device, and that consciousness and self-awareness are essential for human problem solving and communication.

Khan (1998) asked a number of fundamental questions about peoples preferences towards a domestic service robot including appearance (mechanical and rounded), preferred size (about 1m tall), task domains (cleaning, washing, ironing etc., but not childcare or family), communication (verbal), voice style (neutral or female) and autonomy (limited). People indicated that they would tolerate a robot in the home, so long as it enabled them to "achieve more time with the family, more leisure time and to get rid of tedious everyday work". Their preferred description of a robot was as a "smart household appliance". Many of these findings were confirmed by results from our later study which analysed participants responses to questions about preferred robot task domains. Dautenhahn et al. (2005) identifies users as preferring a service or domestic robot primarily to act as a "smart machine". They preferred the robot to exhibit more human-like communication abilities, but did not generally express a desire for the robot to be more human-like in appearance. Users expressed little desire to relate to the robot as a companion and preferred to emphasise control over the robots actions, rather than for the robot to exhibit too much autonomy. The robot behaviour model that seems to be appropriate here is more servant or butler than a "co-operative companion". Scopelliti et al. (2004) surveyed older peoples views and preferences for domestic robots. They seemed to recognise the potential usefulness of robots but were concerned about possible damage and intrusions into their privacy. Overall they preferred a serious looking small robot, with a single cover colour and slow movements. Most of them would prefer it not to be free to wander inside the house and expected it to be programmed in a fixed way to execute specific tasks. When asked about the types of specific tasks the robot could perform in their home their answers tended to be (perhaps not unexpectedly) somewhat vague or unrealistic. These studies have all found evidence that most people would not actually want a domestic or service robot to be too human-like in appearance (cf. Khan (1998) and Dautenhahn et al. (2005)).

Other research has indicated that humans respond to social and non-verbal characteristics, attributes, features or behaviours exhibited by less human-like (mechanoid or humanoid) robots. Nicolescu & Mataric (2001) described a mechanical-looking robot which could communicate intentions by using body movements. Okuno et al. (2002) implemented an auditory and visual (multiple) talker tracking (attention) system and found that it improved the social aspects of human robot interaction for a simple (4 Degree of Freedom) humanoid type robot. A study by Friedman et al. (2003) has shown that while people in many ways view an Aibo robot like a real dog, they do not treat it or view it in precisely the same way as a living dog (e.g. with regard to moral standing). Goetz & Kiesler (2002) found that a robot with a serious, caring personality induced more compliance than a playful, enjoyable robot on a task that consisted of aiding a human companion to carry out exercise as part of physical therapy.

Breazeal (2002) and Breazeal (2004) presented a series of studies which examined how stylised cartoon-like expressive robots can exhibit emotions and interact in a non-verbal social way with humans. Kismet is an expressive robotic head and Leonardo a whole body robot with a pet-like appearance and both are designed to elicit non-verbal social interactions with humans (Figure 4). Most published outcomes from their studies relate mainly to the technical details of implementing various autonomous social expressions, gestures and behaviours on robot platforms to simulate various aspects of human social behaviour. (This is not a trivial task as Leonardo has some 61 degrees of freedom, with 32 of those in the face alone). Despite their technical sophistication, both robots interact with humans mainly in a needy capacity, either to elicit social (adult-child) caring type responses with the human interactor as a teacher, instructor or demonstrator.

Kismet

Leonardo

Figure 4: Expressive Robots used for research into HRI . From Breazeal (2004)

However, Breazeal (2000) has found that humans do respond socially to these robots in some very fundamental non-verbal ways with regard to turn-taking in speech communication and with respect to the robot's interpersonal space. Nomura et al. (2007) found that both participants negative attitudes and anxiety towards a small size humanoid robot, RobovieM (29 cm tall and 1.9 kg), affected the (comfortable) approach distances that they would allow between themselves and the robot.

Hűttenrauch et al. (2006) have analysed spatial relationships in an HRI trial using Wizard of OZ (WoZ, see Section 2.4) techniques, and have concluded that most participants kept a distance from the robot corresponding to Hall's Personal Spatial Zone (0.45m to 1.2m) when communicating and showing the robot objects as part of a simulated home tour scenario. They also found that participants tended to adopt a face-to-face formation when interacting with the robot. In HRI trials involving children and adults, I found that groups of children tended to approach a similar PeopleBot™ robot to similar distances on a first encounter, and a majority also preferred to orientate themselves towards the front of the robot. However, for individual adults approaching the same robot to a comfortable distance, the approach distance preferences were more ambivalent and inconclusive (cf. Walters et al. (2005a)). These particular trial results are presented and discussed more fully in Chapter 3.

2.3.1 Non-Verbal Aspects of Robot Speech Interfaces

Most published research into speech interfaces relates to the use of computer based speech interfaces and animated agents (see the previous section). The systematic investigation of speech systems for robots has been relatively neglected; partly because of the technical problems of using speech, for both recognition and synthesis, on a moving, noisy robot platform in the real world are much greater than those encountered in a static computer or IVE system. However, in recent years, some researchers have begun to look beyond these technical problems to address the issues of how robot voices and speech systems can be used to facilitate communication with robots. The studies which are of interest here are those which focus on human perception and preferences for non verbal aspects of robot voices rather than the majority which address the technical aspects of robot speech generation and understanding (e.g. Lauria et al. (2002) & van Breeman et al. (2003)).

Li et al. (2006) present comparative user study findings for a robot with a dialogue system that can exhibit different verbal and initiative taking behaviours. Their results address various verbal and non-verbal speech behaviours and aspects of domestic social robots. Their initial user studies concentrated on verbal behaviour styles. An extrovert robot dialogue style was rated more positively by trial participants in a home tour scenario HRI trial, than a terse dialogue style. These studies were conducted using WoZ methods (see section 2.4 which discusses HRI trial methodology). In further studies, they have implemented these results into an integrated autonomous system. Li & Wrede (2007) suggest that both useful and social robot capabilities have to be considered together and propose an interaction framework for flexible multi-modality management in complex (dialogue and social behavioural) interactions. They intend to incorporate facial expression in future, in order to use non-verbal means to reflect the robot's internal state (listening, puzzled, understanding, person detected, not-detected etc.)

Böhlen (2007) discusses human prejudices towards synthetic speech production and humanoid robot design, highlighting some of the current ways in which robot speech is disconcerting or annoying to humans. He argues that robots should:

> *"not just be kind and patient, with the capacity to say what we need to know, but also to insistently repeat what we have already heard or do not want to be confronted with."*

He proposes that humanoid robot speech should be qualitatively different from human speech, reflecting the different perception, experience and embodiments of robots and suggests ways in which a richer common communicating experience between humans and robots may be facilitated. He is interested in the roots of annoying speech behaviour and to research this he uses bad-tempered speech robots, Amy and Clara, to investigate language acquisition including accented speech, foul language and misunderstandings! Although it is likely that most people would not want a domestic service robot that argues, swears and forcibly impresses its own view onto human users, findings from this research may eventually highlight the qualities and components of robot speech that people may find annoying.

2.3.2 Robot Appearance

Zebrowitz et al. (2004) investigated how humans make initial, but very strong, assessments of each other mainly on their initial appearances, relying heavily on stereotypes and very general assumptions. Therefore, it is to be expected that initial human perceptions of robots, including their likely social behaviour, will also depend to a large extent on robot appearance. Dautenhahn (2002) has speculated that the best appearance for a robot which interacts with humans may be one that tends towards the more abstract as it would create fewer preconceptions than a robot appearance that was more realistic or iconic. This would be desirable as it would allow humans to accept the robot in a social way, but as something other than an entity which they may have met before (e.g. a human, pet, servant or child.). Others, such as Powers & Kiesler (2006) have equally reasonably argued that preconceptions created by a particular robot appearance or behaviour, can usefully be employed to improve interaction with a robot by humans, in the way that the "Desktop" metaphor of a Graphic User Interface (GUI) facilitates users' interactions with modern computers.

2.3.2.1 Robot Appearance Rating

There are several ways of rating robot appearance. Inspired by Scott McCloud (1993) and his book, "The Design Space of Comics", Dautenhahn (2002) identifies two dimensions with regard to robot appearance: a realistic to iconic scale, and a representational to abstract scale. Any image of a comic agent (character) can be rated along these two scales and plotted as a 2D point in the plane which represents the design space (see Figure 5). This has been applied in the design work for the face of their humanoid robot, KASPAR (cf. Blow et al. (2006) and Blow et al. (2006b), Figure 6). There is a category of isomorphic robots which has appearances which are animal-like and mainly have applications as research, pet, toy and entertainment robots. Their appearances can range from mechanical-like to cartoon-like, abstract or realistic (Figure 7).

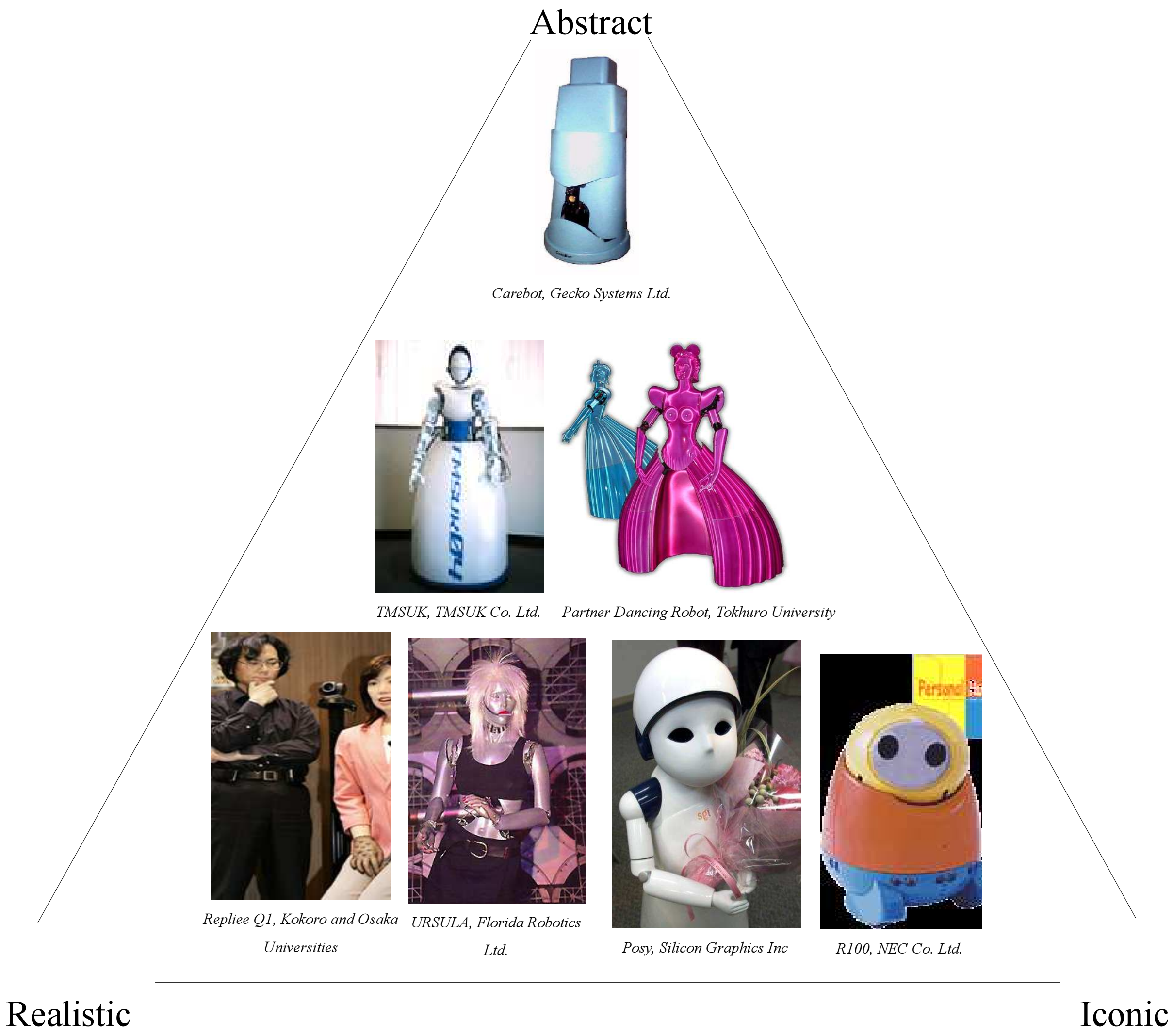
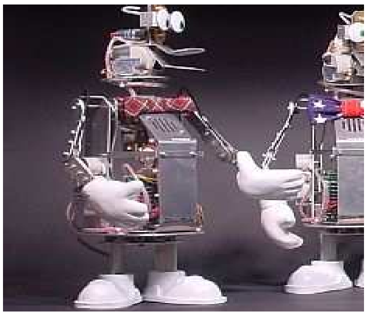


Figure 5: Diagram illustrating Scott McCloud's design space of comics with real life robots, which identifies two dimensions relating to representations of people in comics and cartoons. Based on a Diagram from Dautenhahn (2002)

Figure 6: KASPAR, University of Hertfordshire. Blow et al. (2006b)

Robots may also be placed on an anthropomorphic appearance scale (Figure 8) which varies from a machine-like to a human-like appearance as suggested by Kiesler & Goetz (2002), Goetz et al. (2003) and Woods et al. (2004). Hinds et al. (2004) have studied the effect of the degree of anthropomorphic robot appearance on humans carrying out a joint task with a robot. Findings show that mechanical-looking robots tend to be treated less politely than robots with a more human-like appearance. Also, that humans commonly treat mechanical-looking robots in a subservient way (i.e. less socially interactively) compared to more human-looking robots. Moreover, expectations are in general lower with regard to abilities and reliability for mechanical-looking robots.



MechaRobo Robots, Mytech Ltd.

a)

SAM, Red Magic Ltd

b)

Banryu, Sanyo & TMSUK

c)

AIBO 2, Sony Inc

d)

PARO, Institute of Advanced Industrial Science and Technology, Japan

e)

Robot Cat Necoro, Omron Ltd.

f)

Figure 7: Animal and Pet Robots. Appearances range from abstract a), cartoon-like b), mechanical c) and d), and increasingly realistic e) and f).

Pioneer DX2, ActivMedia Ltd

Industrial Manipulator, Toshiba Inc.

Cleaning Robot, Figla Co. Ltd.

Machine-Like Appearance (Mechanoid)

Humanoid Robot, University of Hertfordshire

Rolling Partner Robot,Toyota Inc

HOAP II, Fujitsu Inc.

Some Human-Like Appearance Features (Humanoid)

Actroid DER2, Kokoro and Osaka Universityies.

Master Lee, YFX Studios

Geminoid HI- , ATR Intelligent Robotics and Communication Laboratories,Kyoto

Human-Like Appearance (Android)

Figure 8: Mechanical-Like to Human-Like Appearances Scale for Robots

2.3.2.2 *Robot Appearance Preferences*

The form of socially acceptable robot behaviour to be exhibited by any particular robot will be dependent not only on the task, context and interaction situation, but also on the robot's appearance. Woods et al. (2004) investigated children's preferences and ratings of robot appearances and compared them to adults' views in a comprehensive survey using some 70 images of (static) robot appearances varying from pure machine-like (Mechanoid) to very human-like (Android). The findings indicate that both adults and children did not like very human-like robots. The children rated both human-like and machine-like robots as aggressive, machine-like robots as angry, and part-human-like (humanoid) robots as most friendly. There was a high level of agreement between the adult and child groups' preferences for robot appearance, though the reasons given by each group for their choices were different. Children based their choices on the perceived aggressiveness (negatively), anger (negatively) and friendliness (positively). Adults tended to base their choice primarily on the understandability of the robot. It seems that children generally agreed in their ratings of robot personalities and emotions across the different robot appearances. In other words, children tended to like the same perceived personality and emotion attributes, and were also able to rate these attributes for the different robot appearances.

Lohse et al. (2007) have conducted an exploratory study into people's preferences for four different robot types; BIRON, a human scaled robot of mechanical appearance (based on the commercially available mobile PeopleBot™ platform); Barthoc, a humanoid robot; AIBO, the Sony robot dog and iCAT, a commercially available yellow cat-like research robot from Philips (Figure 9). Both BIRON and Barthoc were seen as "serious" robots, and AIBO and iCAT primarily as toys. People rated the zoomorphic robots AIBO and iCAT as most likeable and rated the humanoid Barthoc robot as least likeable. They found interacting with AIBO and iCAT most enjoyable, but actually preferred to "use" BIRON most, which probably indicated that they perceived BIRON as being the best combination of useful and enjoyable. The robot Barthoc had a realistic human-like face mounted on a mechanical body which may have been perceived by participants as disconcerting. This effect is discussed in more detail in the following section.

ICAT, Phillips Ltd.

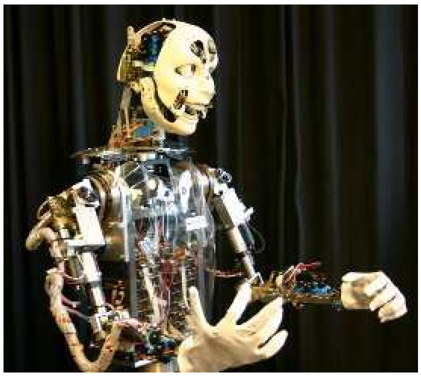
a)

AIBO 2, Sony Corp.

b)

Barthoc, University of Bielefeld

c)



Barthoc, University of Bielefeld

d)

BIRON,University of Bielefeld

e)

Figure 9: The four robots used for the study by Lohse et al. (2007).: a) iCAT, b) AIBO, c) and d) Barthoc, and e) BIRON

These findings generally confirm those by Khan (1998) who found that people generally preferred more mechanical-looking (mechanoid or humanoid) domestic or service robots, with a rounded shape and a serious personality.

2.3.2.3 Mechanical and Human-Like appearance

Most currently commercially available research robots tend to have a somewhat mechanical appearance, though some have incorporated various humanoid features such as arms, faces, eyes and so on. Some research robots, often referred to as androids, are very human-like in appearance, though their movements and behaviour falls far short of emulating that of real humans. Mori (1970) proposed a general effect in which people will act in a more familiar way towards robots as they exhibit increasingly human-like characteristics. However at a certain point the effect becomes repulsive due to robots that look very human-like, but their behaviour identifies them as robots. This proposed effect can be illustrated by means of Mori's diagram (see Figure 10) where the shape of the curves gives rise to the term 'uncanny valley' to describe the repulsive effect. Mori's original proposal indicated that the 'uncanny valley' effect was present for inanimate likenesses, but was even more pronounced for robots, puppets and automata which actually exhibit movement. Therefore, according to Mori, although robot appearance is important with regard to familiarity and social acceptance, the actual quality and content of a robot's movements are even more important. Mori argued that robot appearance and behaviour must be consistent with each other. At the extreme of high fidelity appearance, even slight inconsistencies in appearance and behaviour can be powerfully unsettling and cause a large repulsive effect.

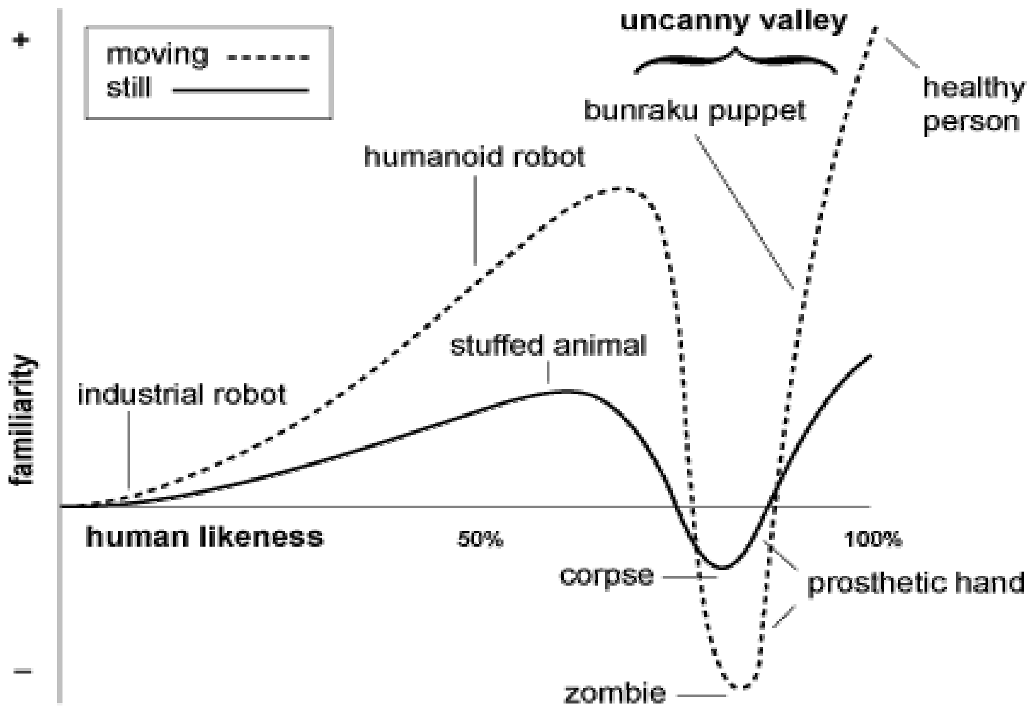


Figure 10: Mori's uncanny valley diagram (simplified and translated by MacDorman (2005))

It has been postulated by animal behaviourists that a heightened sensitivity to small discontinuities in appearance (and behaviour) may enable the rapid detection of diseased individuals of the same species and hence the reaction of increased approach distance for fear of contracting the disease. This may also explain the powerful disgust reaction that has been observed when distorted faces have been shown to humans (cf. MacDorman & Ishiguro (2006)). The 'uncanny valley' effect is not uncontroversial, and some roboticists such as Ferber (2003) and Hanson et al. (2005), have argued that there is conflicting evidence for the right hand side of Mori's "Uncanny Valley" diagram. However, much anecdotal evidence from practitioners in Computer Generated Imagery (CGI), film effects and sculpture seems to support Mori's original conjecture on the uncanny valley. The possible underlying reasons are discussed by Brenton et al. (2005). More recently, Bethal & Murphy (2006) have identified some ways in which very mechanical looking (search and rescue) robots can use appropriate 'body movements' and postures to provide useful non-verbal expressions of non-threatening and re-assuring behaviour, and also avoid appearing threatening or 'creepy' to (trapped) humans being rescued. The participants' anxiety levels toward robots also changed after the experiment session depending on the robot's walking speed. The fact that mechanical looking rescue robots can sometimes appear threatening to, or provoke anxiety in (non-familiar) humans also lends some credence to more recent assertions by Hanson (2006) who argues that even non-human-like robots with an abstract appearance can exhibit the uncanny effect if the "aesthetic is off" in a similar way that can occur with cosmetically atypical humans.

Research continues into the area of very human-like robots or androids. For example, Minato et al. (2004) and Ishiguro (2007) have built android robots: a) to study how humans interact with robots which have a very human-like appearance and b) in order to gain insights into human cognition. Inspired by the original theory of Mori (1970), Minato et al. (2004) have proposed that if a particular robot's appearance and associated behaviour were consistent and more human-like, but not to the extent that the 'uncanny valley' was reached, it would be more acceptable and effective at interacting with people (cf. MacDorman (2005), Woods et al. (2004)). However, Goetz et al. (2003) also argued that appearance should be matched to the type of task that a robot is to perform, and as such the degree of human-likeness which is desirable for any given role or task may vary.

Lee & Keisler (2005) have examined how humans form a mental model of a (humanoid) robot by making unconscious assumptions from the robot's attributes and features within a very short period of exposure. The mental model is then used by the human as a guide as to the likely state, knowledge, capabilities and performance to be expected from a particular robot. If the appearance and the behaviour of the robot are more advanced than the true state of the robot, then people will tend to judge the robot as dishonest as the (social) signals being emitted by the robot, and unconsciously assessed by humans, will be misleading. On the other hand, if the appearance and behaviour of the robot are unconsciously signalling that the robot is less attentive, socially or physically capable than it actually is, then humans may misunderstand or not take advantage of the robot to its full abilities.

Kanda et al. (2007) have investigated some of these issues with a robot which (pretended to) listen to a human user when the human was providing route directions to the robot. When the robot exhibited social behaviours, such as eye contact, head nodding and arm movements, the users had a greater impression of the robot paying attention, of reliability and sympathy, and understanding the directions correctly than when the robot did not exhibit these behaviours. In a comparable real life situation, a robot could advantageously make appropriate social (behaviour) signals to reinforce or indicate that it had genuinely understood correctly or otherwise.

In a previous study where robots interacted with children in a game scenario, we have found that the children's attention is attracted more by a robot pointing arm and camera movement when they are consistent with each other (cf. te Boekhorst et al. (2006)). Bruce et al. (2002) studied a robot which exhibited both appearance (a facial expression) and behaviour (turning movement) cues. Findings showed that the cues were more effective at gaining people's attention when both were used together consistently. However, in a similar experiment, Finke et al. (2005) found that a mechanoid robot (with no facial features) which exhibited a turning movement towards an approaching person, did not achieve any more attention from passers by in a corridor than the same robot did when it was static. However, the authors admit that the turning motion was some 4 or 5 seconds after the approaching person was recognised, and many people had already looked at the robot and moved on during this time. They suggest that a quicker robot turning response combined with robot speech may have attracted the attention of passers-by more reliably. In other words, the use of two or more consistent behaviours would be more effective than just the one attention attracting behaviour. Also, the fact that the turning behaviour was not performed at the opportune moment may have contributed to passers-by perceiving the robot as exhibiting inconsistent (temporally displaced or retarded) behaviour.

The studies reviewed here, including those which investigated humans, computer animated agents and the relatively few that have investigated how robots are perceived by humans, indicate that humans are very sensitive to perceived inconsistencies between appearance and behaviour. It is likely therefore that robots which are perceived as having consistent appearance and behaviour will be assessed more positively for a number of factors than robots which have inconsistent appearances and behaviours. However, how humans judge a set of particular robot attributes for appearance and behavioural consistency is an open question at present. Practically all attempts to create a robot with consistent appearance and behaviour have been the result of inspired guess work. Designers and artists who create robot characters for science fiction films and comics have probably spent most time designing robots which are perceived in appropriate ways (e.g. scary, dumb, friendly). However, almost certainly much of this design work is based on trial and error, though some general guidelines exist (e.g. McCloud (1993)).

2.4 HRI Experimental Trial Methodology

HRI trials usually involve a large amount of effort to plan, set-up and carry out. They require the combined work of a multi-disciplinary team, with a mixture of skills and backgrounds and interests including robotics, psychology, and computer science and engineering. To illustrate the effort involved, one of the main HRI trial series (as described in Chapter 1, Table 2 and Chapter 4.2) is used here as an example. This particular HRI trial series included 42 participants undergoing interactive sessions, each lasting approximately one hour including questionnaires, with approximately 30 minutes of actual HRI "contact time". Developing these trials occupied a team of three researchers full-time for a period of about three months (spread over a pre-trial period of six months) to do the necessary pre-trial set-up and organisation. This included robot and systems software and hardware development, questionnaire development and testing, pre-trial and pilot testing before the trial proper could run. The actual trials ran over the course of four weeks. Effectively, running this one trial series for a participant sample size of 42 took approximately 12 person months in total. Our efficiency at running trial sessions has improved over the period of this study, although the set-up time is still typically several months. For an early set of exploratory HRI trials we managed to do only 28 x 1 hour HRI sessions over five weeks (cf. Chapter 3.2). However, for the last set of HRI trials (see Chapter 6) we managed to run over 120 x 1 hour sessions in total over five weeks! As these examples illustrate, the effort involved in running a controlled set of live HRI trials is considerable. As such, a single set of trials will usually incorporate a number of individual experiments investigating various aspects of a particular HRI scenario or situation according to the interests and requirements of the research team. Of course, these individual experimental results can often be combined and analysed together to obtain new perspectives. HRI Trial methodology development is therefore vital to gain valid data in order to explore, support, develop and test new theories in HRI.

2.4.1 HRI Trials: Experimental Set-up and Procedures

The University of Hertfordshire COGNIRON Project Team are one of the most experienced teams in the world currently at running full scale HRI trials with human-scaled robots in experimentally complex controlled live interaction scenarios. Walters et al. (2005) discuss our experiences of running two initial exploratory trials with humans and robots physically interacting and highlights problems encountered (see Chapter 3 for other details). The discussion covers practical aspects of running live trials with humans and robots interacting in a shared area. A set of guidelines for running HRI trials are provided under the following headings:

1. *Risk* - The main priority in any HRI trial is the human participant's safety. Physical risk cannot be eliminated altogether, but can be minimised to an acceptable level by means of a proper risk assessment. In this way, the risk of a collision with a participant is minimised, though there is still the risk that participants may initiate a collision with a robot, accidentally or otherwise, due to their faster movements.

2. *Ethical* - Different countries have differing legal requirements, which must be complied with. The host institution may also have additional requirements, often within a formal policy. For example, the University of Hertfordshire (2006) requires that any scientific experiment which involves the use of human participants must be formally approved by the University Ethics Committee. When using WoZ HRI trial methods, trial procedures with regard to what and when to tell participants about the deception involved must be laid down.

3. *Robot Behaviour* - Ways are suggested in which robots can be programmed or controlled to provide intrinsically safe behaviour while carrying out human-robot interaction sessions (see below, Section 2.4.1.1). For example, we have advocated the use of robots with intrinsically safe collision avoidance behaviour which overrides all other operator generated control commands and programmed task actions. It is good practice to have a backup robot available.

4. *Video Records* - The paper discusses the advantages of different types of video cameras and suggests ways to optimise camera placement and therefore maximise coverage. In the course of our more recent work we have developed automatic video based data collection and annotation techniques (see Walters et al. (2007), Walters et al. (2007b))

5. *Questionnaire Design* - Guidelines are provided to enable the design of trial questionnaires, and the paper highlights a number of relevant points to consider when developing questionnaires specifically for HRI trials. The main requirement is to avoid influencing questionnaire results by poor question design, and some examples of both good and bad practice are provided in order to illustrate these points.

6. *Pilot Trials* - Sufficient time should be allowed for piloting and testing any planned trials properly in order to identify deficiencies and make improvements before the trials start properly. Full scale pre-test and pilot studies will expose problems that are not apparent when running individual tests on the experimental equipment and methods.

HRI trials commonly use a WoZ method for controlling robots during an HRI session. This is a method of using robots fully or partially controlled by hidden or disguised operators in order to produce robot capabilities and behaviour that would be difficult or even technically impossible using current robot systems. The advantage of WoZ methods is that they allow for proposed robot behaviours and capabilities to be pre-tested for effectiveness and usability before investing considerable time and expense in developing and implementing them in a live robot system. Green et al. (2004) discusses the WoZ methodology in detail and highlight a range of practical, technical and ethical issues that arise when applying the WoZ framework to HRI trials in the context of a service robotics scenario, involving a collaborative service discovery and multi-modal (verbal and non-verbal) dialogue with the robot. Techniques of using WoZ operators to produce synchronised dialogue and robot movements are reviewed. In a later paper Green et al. (2006) describe and discuss how "Hi-Fidelity" simulation methods (WoZ methods) were employed in a user-centred approach to develop natural language user interfaces for robots. They state that data obtained from Hi-Fi simulation studies is primarily qualitative, but may also be used for quantitative evaluation depending on the experiment design. The recorded data in this case study was also be used for robot system development (e.g. training data for speech recognizers).

Sabanovic et al. (2006) discuss and recommend the use of observational studies of human-robot social interaction in open human-inhabited environments as a method for improving on the design and evaluating the interactive capabilities of social robots. They argue that the best way to evaluate how humans interact with robots is in a "natural" setting (as opposed to "controlled" laboratory-based experiments) and show how observational studies can be applied to human-robot social interactions in varying contexts. They review two observational studies of robots interacting socially with humans: The first is an analysis of a mobile conference-attending robot that performed a search task by augmenting its perception through social interaction with human attendees. The second is an analysis of a stationary robotic receptionist that provides information to visitors and enhances interaction through story-telling. They quantitatively and qualitatively evaluate (and discover unanticipated aspects of) the human-robot (social) interactions.

The use of a naturalistic behavioural observation methodology does require as a (practical) necessary pre-condition a working robot which can operate autonomously for extended periods of time. The two studies they use as demonstrations of the method used relatively static applications of robots (e.g. the robot receptionist could draw power through a cable link). Few mobile research robots can operate on battery power for more than a few hours continuously at present. With extended exposures of robots to humans, the use of WoZ methods becomes problematic, due to operator fatigue and maintaining concentration by the operators over long periods. This implies the use of autonomous (or at least semi-autonomous) robot behaviour for these observational type HRI studies. The current state of robot technology only really supports (safe) interaction with humans under relatively well defined situations. Examples include a robot receptionist (see Gockley et al. (2005) & Sabanovic et al. (2006)) or museum guides and entertainers (Figure 11. See Schraft et al. (2000) & Shiomi et al. (2007))

Figure 11: The Fraunhofer IPA Interactive Museum Robots. cf. Schraft et al. (2000)

2.4.1.1 The UH COGNIRON Project Team: Our HRI Trial Experience.

We have provided robot demonstrations at the Science Museum in London in 2005 where we ran interactive games for children aged mostly from 3 to 10 years old (See Figure 12). We used a PeopleBot™ robot in its standard configuration. The lifting gripper manipulator was adapted to form a basket to carry the "prize" and point to the winner in a "pass the parcel" party game. The robot ran fully autonomously for around 20 minutes for each session with each group of approximately 40 children at a time, who were seated in a circle around the robot. The arena formed a clear boundary for the robot, which was programmed with intrinsic safety "collision avoidance" behaviours which were designed to override the main game "task" script instructions. This provided robust fail-safe operation by the robot over two days of repeated interactive game sessions.

Figure 12: Interactive games for children at the London Science Museum. Run by COGNIRON Project Team members from the University of Hertfordshire (http://news.bbc.co.uk/2/hi/technology/3962699.stm)

Participants' safety in any HRI trial or demonstration is of course paramount and the development of the robot game program was adapted from previous programs used in our first HRI trials (see Chapter 3 and Appendix IV). Even so it required two solid weeks of further testing and debugging to ensure safe and reliable autonomous operation (with our long suffering colleagues taking the place of the children!). For our interactive games in the Science Museum, we stood by to stop the robot via a wireless link (or as a last resort a manual "kill" emergency stop switch) in case of faulty operation of the robot. Fortunately, no intervention by us was required and the robot operated as anticipated!

For all the various HRI trials, events and demonstrations we have run, including those for this study, we have used two PeopleBot™ mobile robots from ActivMedia Robotics Ltd. These are ready-made research robot mobile platforms and are used widely by other researchers in the HRI field, and in particular by some other partner members of the COGNIRON consortium. The full technical specification can be found on the ActivMedia Robotics website (www.activrobots.com) but brief details are given here:

The PeopleBot™ has a 47 cm x 38 cm x 112 cm aluminium body, which runs on two 19 cm dia main drive wheels with differential drive and can carry a 13 kg payload. A rear caster balances the robot, which can climb a 5% grade and sills of 1.5 cm. On a flat floor it can move safely at speeds of .8 m/s. The robots include 24 ultrasonic transducer (range-finding sonar) sensors arranged to provide 360-degree coverage from 15 cm to approximately 7 m. Our robots have an optional embedded LINUX computer which runs the ARIA robot Operating System (OS) control software. The robot base micro-controller has user I/O accessible through ARIA. The robots also include fixed IR with range of 50 mm to 1000 mm to sense the underside of tables. The built-in lifting gripper has a payload capacity of 1 kg (2.2 lbs.) and is used in our robots either for actuating our pointing arm, or for mounting a carrying tray (Figure 12). Our PeopleBot™ robots are equipped with a Pan and Tilt Unit (PTU) fitted with a video camera which can be used to send on-board video to a remote screen by wireless network link, or for further utilisation by the robot (e.g. for object recognition, navigation, localisation). The robot can be controlled remotely over the wireless network link.

For the various HRI trials, we have made hardware modifications and add-ons to provide specific appearance features and behaviours. We have also developed our own autonomous and semi-autonomous control programs for the platform. More details of these are given in Chapters 4, 5, 6 and Appendices I to IV.

2.4.2 Behavioural Based HRI Trial Data

A common method adopted to obtain data in human psychological and behavioural studies is for trained observers to annotate trial sessions directly using a pre-determined coding system. With the easy availability of video recording equipment, it is more usual now to observe video recordings of trial sessions, looking for behavioural cues and actions (expressions, gestures, eyes gaze direction etc.) and temporally annotate these in synchronisation with other related events happening on the video at regular sample intervals (typically 1 second or so). A range of quantitative statistical tests can then be performed on this data to obtain insights into how human participants respond to trial conditions, scenarios and situations. This method has also been used successfully for HRI trial data analyses.

Tanaka et al. (2006) present results from an ambitious long term study performed for 45 days over 3 months in the uncontrolled conditions of a child-care centre. The results related to children's interactions with a small humanoid dance robot. They used continuous audience response methods borrowed from marketing research (based on human rating and annotating videos of the child-robot interactions) and reported reliable results. They also experimented with objective behavioural descriptions, such as tracking children's movement across the room and temporal measurements (e.g. interaction duration and timings) which provided a useful picture of the temporal dynamics of the child-robot interactions through the trials. It seems that much of the (video-based) data collected for this HRI trial awaits further analysis. We have performed a similar analyses on video data collected from a series of HRI trials run with groups of children who participated in interactive games with a PeopleBot™ robot and te Boekhorst et al. (2006) present the findings from the video coding and a full description of the trial procedure. Separate experiments relevant to the current study were also incorporated in this particular trial, and are presented in Chapter 3, where a fuller description of the trial procedure can also be found (see Walters et al. (2005a) & Walters et al. (2006)). It should be noted that the work involved in performing this type of video based behavioural analysis is intensive, especially for long-term trials when many hours of video recordings need to be coded separately and repeatedly by several coders in order to ensure reliability in the annotations.

Combining human-observed behavioural-coded data with automatic sensor-measured data can provide an independent (objective) measure of human behaviour. For example Salter et al. (2004) demonstrate that infra-red sensors located on robots can be used to detect and distinguish children's play behaviours. They used a close behavioural analysis of the recorded video data in conjunction with the infra-red (IR) sensor contact data, to yield patterns of interaction from individual children when interacting with the robot. This initial analysis was time-consuming and was performed off-line. However, once the forms of the relationships between (the relatively simple and easily obtained) robot IR sensor readings and child behaviour has been established, the robot potentially could sense the child play behaviour directly. François et al. (2007) have been investigating how such a robot could interpret interactors' movement and interaction or play styles in real time and thus adapt its play responses appropriately in order to aid therapy or rehabilitation.

The use of sensor data can also be used to ease the burden when hand annotating HRI trial sessions. Hűttenrauch et al. (2006) have developed a method of hand video coding combined with robot-derived laser range sensor data. Still images are clipped from the video data at specific times related to the context and actions being performed in the HRI trial scenario as assessed by trained observers. These are then overlaid with another image from the same camera viewpoint which contains a metric grid on the floor. This allows the distance and orientation between human participant and robot at the point to be estimated at these specific points of the interaction. These are then verified against the robot's laser range data to obtain a more precise measurement of both the participant's distance and orientation with regard to the robot. In this case the estimated distances were coded according to which of Hall's spatial zone (intimate, personal or social) they happened to fall, but this method could be used to obtain precise quantitative scale distance data. This method is much less labour intensive than full (video-coded) behavioural analysis of video recordings, but it can only be used where the rating measure can be objectively defined (in this case distance, verified by the robot range sensor).

Other types of automatic sensor data that have been used with some success in HRI trials include Galvanic Skin Response (GSR) and skin temperature sensors. Mower et al. (2007)

report a high level of success (over 80% effective over the trial period) in rating users' engagement state with a robot (which exhibited different personalities) in a wire puzzle game scenario. Hanajima et al. (2005) also reported using Electro-Dermal Activity (EDA = GSR) measurements to obtain ratings of users' stress when an industrial robot manipulator was moved and approached seated participants. They reported however, that the measurements were affected by ambient conditions and individual variations. In both these trials, repeated measures (often over several sessions) were required to factor out spurious results and obtain the underlying GSR responses related to the robot movements. Kidd & Breazeal (2005a) report a similar experience when using GSR methods and have discouraged their use in real-time adaptive robotic applications due to the difficulties in relating a particular GSR reading to any particular event.

2.4.3 Self-Reporting HRI Trial Data Collection methods

Probably the main method of obtaining trial data, which has been adopted by HRI trial researchers from the field of psychological field trials, is the use of questionnaire methods and, to a lesser extent, structured interviews (cf. Harrigan et al. (2005)). These methods allow trial participants to provide subjective feedback with regard to their perceptions and feelings about a wide range of aspects of their trial experiences. Practically every reported user study in the field of HRI has used some form of questionnaire to obtain at least some measure of participant self-reported responses. Typically the particular questions require participants to respond in one of three possible ways: *Qualitative response* - Participants provide a sentence with an individual and descriptive response. (E.g. "Give reasons why you liked this robot the most?"). These results may be grouped by main responses, terms and themes and the respective frequencies examined to provide overall qualitative impressions. *Overall preference* - a multiple choice selection response was presented (E.g. : "Which was your most preferred robot? Choose answer from: A, B , C or D:"). *Quantitative ordinal ratings* - Typically uses a four or five point Likert scale (cf. Likert (1932)) to obtain ratings (E.g. "How much did you like robot A?" Response from: 1 = Not at all, 2 = Not much, 3 = Neutral, 4 = A bit, 5 = A lot). These responses can be subjected to a wide variety of non-parametric statistical tests for significance (e.g. Walters et al. (2008a)). The same basic principles also apply to participants' responses to questions posed during structured interviews. However, due to the contingent and open ended nature of (structured) interviews, the data tends to be biased towards being descriptive and qualitative.

2.5 Discussion of the Literature Review

The discussion of this literature review is considered in three parts relating broadly to the main subject areas and disciplines which contribute to this study.

2.5.1 Human-Robot Proxemics Behaviour

Practically all robots which need to work in the same area as humans have a selection of proximity sensors, including sonar, infra-red and laser range sensors. Measurement of human-robot distances and orientation in real time is now robust and straightforward to implement, even on relatively simple mobile robots. Therefore proxemic data is readily sensed and available from robots' internal sensors, often as a by product of the navigation system. If this proxemic data can also be used to estimate, indicate and communicate other information about interacting humans, then this would make even better use of robots' existing sensor data.

Most previous studies which have considered Human-Robot Proximity have mainly based their analyses on the broad categorisations of distances into Hall's social spatial zones. However, Hall's social zone distances were based on rough visual estimates of contact, arm reach and handing-over and potential attack distances. However, this review of human-human proxemics has indicated that there is a far richer body of research results which shows that proxemic distances between humans can also be affected by, and are indicative of, a number of other factors. Physical proximity between humans can be affected quite drastically by the environment (open, restricted physically, corridor etc.), the relative status of interactors, uncertainty (mild perceived threat etc.) and subtle manipulations of the proxemic distance by interactors to send coded social messages to each other (threat, status, insult, respect etc.). The distances over which these factors operate are usually at a finer grain than Hall's broad social zones. It was therefore seen as a worthwhile aim for the initial part of this study to investigate which of these factors, or perhaps different factors, might apply to HRIs.

2.5.2 Measurement of HR Proxemic distances

It has been noted previously in this chapter, that the field of Human-Human proxemics has not agreed on a standard way to measure human-human proxemic distances (see Chapter 2.2 & Harrigan et al. (2005)). As human-robot interpersonal distance was proposed as an indicator for peoples perceptions of robots with regard to non-verbal behaviour, it is necessary here to define a measurement standard for HR interpersonal distance to be used for all the experiments to be performed for this thesis. It is also desirable that all proxemic distances measurements for this study are approximately comparable to those made by Horowitz et al. (1964), Sommer (1969), Stratton et al. (1973) and Hall (1974).

Hall's social zones are most frequently referred to in HRI proxemic studies, so it is useful to use here an interpersonal distance measurement method that is comparable. As a starting point to developing such a standard, it should be noted that Hall's original social spatial zone distances were given in qualitative terms only and were related to peoples (estimated) contact, arm reach and arm length distances. In order to make approach distance measurements that were roughly comparable to Hall's social zones, but more importantly to able to be make the measurement with a high degree of repeatability. It was noted that a Hall distance of zero (contact) implies that the interacting bodies were touching. Therefore, a Hall social zone distance of say, 45cm is the distance between the closest *boundaries* of the trunk areas of two interacting humans' bodies. Therefore, to provide directly comparable HR proxemic measurements for all proxemic experiments performed for this thesis, all distance measurements were made between the closest body parts of robot and participant, but not including arms or manipulators. Where such a standard measurement was impracticable, or were made using some other datum or baseline (e.g. using the on-board robot sensors), then measurements obtained were corrected by applying suitable conversion factors and constants to obtain the equivalent standard distance measurements.

2.5.3 Consistency in Robot Appearance and Behaviour

A theme that recurs in all the discussions and speculations about Mori's 'uncanny valley', task domains, robot appearance and social behaviour is the desirability of the perception of consistency between the robot appearance and behaviour. That is, the robot should behave both socially and, with regard to both functional and task capabilities, in a way which is consistent with its appearance. This is supported by the findings from the associated field of HCI, with reports of animated agents being rated as more preferred, trustworthy and honest when it is perceived that their appearance and behaviours are consistent with each other (see Section 2.2).

People are very sensitive to very small imperfections in appearance, and especially perceived inconsistencies between behaviour and appearance, both for animated agents and androids with a realistic high fidelity appearance. It is probable therefore, that the best appearance for a domestic robot is more mechanical-like (mechanoid or humanoid) than realistically human (android). This is supported by survey results which reveal that most people say they would prefer a domestic robot to have an overall mechanical appearance with some human-like features to facilitate more natural (possibly speech-based) communication. How to define, recognise and design a set of robot social behaviours which are perceived by people as consistent with each other for a particular robot appearance has not been addressed previously and what would be an optimum appearance for a domestic robot is still an open question. It is likely also that people's individual preferences for a domestic robot appearance would differ. Therefore another interesting initial research question would be:

> *Are there are common factors with regard to people's preferences for robot appearance?*

It is therefore proposed that the overall appearances of robots to be investigated with regard to the above research question should be limited to mechanoid and humanoid robots, as previous research from the fields of HCI and HRI indicates that people do not want robots that are realistically human-like in appearance.

2.5.4 Methodology

The existing body of human interaction research has provided an excellent guide to the development of appropriate research methods in the closely allied field of Human-Computer Interaction user trials, and also in recent years for the relatively new field of Human-Robot Interaction. Experimentally tried and tested methodologies which are commonly used to investigate human studies into non-verbal behaviour can therefore be adapted and used for HRI trials investigating human-robot non-verbal interaction. Harrigan et al. (2005) provide an excellent source for up to date research methods in the field of human non-verbal interaction research, which can be readily adapted for equivalent experimental tests in HRI.

The observations of Sabanovic et al. (2006) are very pertinent. It would be very desirable to perform observation studies of humans interacting with robots in everyday "natural" situations in the same way that such observational studies have become vital to research in both human and animal behaviour studies . This would certainly provide more valid results, as the interactions would be undoubtedly realistically perceived by the human interactors. However, this is not yet a practical method for many types of HRI user trial at present, due to the technical limitations of current robots in performing autonomously in more complex interaction scenarios. These can be overcome to some extent by the use of WoZ methods, but for more extended periods of interaction, the observational methodology would require more autonomous interaction from robots. For the examples presented in Sabanovic's study, the robots were autonomous but the task domains and working areas were well defined and the range and types of interaction were relatively structured and limited, both for content and duration. This allowed the possible courses of the interactions to be anticipated, and thus the robot was able to cope with contingencies in a reasonably robust manner. In more complex situations, the number of different paths through an interaction increases exponentially and it becomes impossible to anticipate and prepare preprogrammed or scripted responses to all possible contingencies.

We and others (e.g. Walters et al. (2005) & Green et al. (2006)) have used semi-autonomous methods in HRI trials to extend the existing limited autonomous capabilities of current robots in order to look ahead, test and guide the HRI aspects of possible and planned advances in autonomous robot capabilities. The technical challenge for HRI trials using interactive robots is therefore to obtain robust robot autonomic responses in HRI situations that may exhibit a high level of contingency and the resultant exponential increase in the number of possible decisions required. As robots become more capable of sustained and flexible autonomous interactions, WoZ augmented autonomy methods can be used to extend and explore yet more sophisticated HRI scenarios by observational and other methods.

The use of sensor-based HRI trial data collection can automatically provide quantitative data for subsequent analyses. The advantages of using automatic sensors systems are that the data is easily accessed and readily imported into statistical analysis packages and spreadsheets for further processing. The use of possibly subjective human raters and coders, and the time-consuming part of manual observation, confirmation and verification is avoided or reduced. If the sensors are mounted on the robot system itself, then the robot has direct access to the information that can be gained from the data. In this way the robot could adapt or modify its behaviour or responses directly in response to the situation and context in real time.

2.6 Summary and Conclusions

A major conclusion from this literature review is that an understanding of human-robot proxemic and social behaviour is crucial for humans to accept robots as domestic or servants. Previous surveys into preferred appearance for a domestic service robot have found that most people do not want a realistic human-like appearance, but would prefer to communicate with a robot by using of human-like speech. They seem to prefer a robot that behaves more like a servant than a companion or friend. However, in common with computers and other artefacts, it seems very likely that the robot will be treated in a social way by the human residents of a household. In order to avoid annoying or upsetting people in their own home a domestic robot will have to exhibit appropriate non-verbal social behaviour.

Most robots have the ability to sense the distance of people and objects in their vicinity. Proxemic behaviour is an important aspect of human social perceptions and communications, but previous HRI studies have mainly concentrated on analyses based mainly on Hall's social spacial zones. It would be desirable to see if some or any of the richness of human-human social spatial behaviour can apply to human and robots. Therefore, the proposed first part of the study was to replicate early human-human studies which investigated how humans approached other humans to comfortable distances (e.g. Sommer (1969), Horowitz et al. (1970) & Stratton et al. (1973)). A standard method of measuring HR proxemic distance was specified for all experiments to be performed for this thesis.

Results and findings from these exploratory trials should then be used to design and implement a more comprehensive set of HRI trials which would address the issues and questions raised. It was appreciated that there were also allied issues of consistency between robot appearance and behaviour which were (and are) seen as important, but not well understood. In order to address these issues and research questions, it was recognised that it would be necessary to develop novel experimental set-ups, HRI trial data collection methods and analytical methodologies. Once the necessary methodological developments had been made and verified, a major set of live HRI trials would then be carried out in order to investigate human perceptions and preferences for robot appearance, non-verbal social and proxemic behaviour under multiple controlled conditions, including combinations of robot interaction context and situation.

Chapter 3: Initial Studies: Human-Robot Proximity

The study of socially interactive robots is relatively new and experimenters in the field commonly use existing research into human-human social interactions as a starting point. From the conclusions reached as a result of the comprehensive literature review in Chapter 2, I assumed that robots are perceived by humans in a social way and therefore that humans will respond to robots in a social way. There may be some similarities with the ways that humans respond socially to a pet, another human, or a child or infant. However, while the aim of many robot designers is to create robots that will interact socially with humans, as argued previously in Chapter 2, it is probable that humans will *not* react socially to robots in *exactly the same way* that they would react to another human. It is probable that a number of factors including robot appearance and behaviour, proximity, task context and the human user's personality will all potentially affect humans' social perceptions of robots. However, as a practical necessity for the first stage in the experimental research, the number of factors under investigation were limited. All the experiments reported in this chapter applied a human-centred perspective, which is concerned with how people react to and interpret a robot's appearance and/or behaviour. This is regardless of the cognitive processes that might happen inside the robot (the robot-centred perspective).

Proxemics is an important aspect of human-robot social interaction, primarily due to the physical embodiment of robots, and also because there was evidence from virtual environments and existing HRI research indicating that humans respected personal space with regard to both IVE animated agents and robots. As a first step in the investigation of how humans perceive and respond to social robots, some of the early experiments into human comfortable approach distances were duplicated (cf. Horowitz et al. (1964), Sommer (1969) & Stratton et al. (1973)) with the robot in place of a human interactor. Humans were invited to approach a robot to a distance which they perceived as comfortable in order to see if people respected the interpersonal spaces of robots. The same experiment was also performed with robots approaching humans.

Figure 13: The PeopleBotTM robot fitted with arm and hand. This robot was used in the IPE study

The broad categories of generally recognized interpersonal social space zones between humans are derived from Hall (1968) and Hall (1974) (cf. Chapter 2, Table 2). The research hypothesis advanced for empirically testing in these initial HRI trials was:

Human-robot interpersonal distances would be comparable to those found for human-human interpersonal distances (cf. Hall (1968)).

The robots used for these studies were commercially available PeopleBot™ research robots from ActivMedia. Their height was designed to be human scaled (1.2m), but both had a mechanical-like (mechanoid) appearance, and in their standard configuration exhibited no explicitly human-like (humanoid) features. Each was fitted with a pan and tilt unit, with a video camera mounted on the top of the robot, and a simple lifting gripper (Figure 13). For all the HRI trials presented in this Chapter, a simple one Degree of Freedom lifting/pointing arm was added to the robot. For the first experiment described in this Chapter which involved children, a soft foam pink hand was added for safety reasons and to aid visibility. For the later two trials involving adults, the hand was replaced with a simple hook which allowed the robot to pick up and carry small objects by means of small colour coded pallets for other experiments in the trials which were not directly relevant to this study (cf. Woods et al. (2005), Woods et al. (2005a), Koay et al. (2005), Koay et al. (2006) & Dautenhahn et al. (2005)).

3.1 Human-Robot Comfortable Approach Distances

It was expected that in scenarios designed for direct human-robot interaction, people would assume distances that corresponded to Hall's Social or Personal zones (similar to the distances people use when having face-to-face conversations) thus treating the robot in a social way with regard to interpersonal spaces. Three separate exploratory HR proximity experiments are presented here, and were carried out using our commercially available, human-scaled, PeopleBot™ robots. The first study took advantage of a larger software evaluation event, run by the FP5 European Project VICTEC (2003), by providing 30-minute sessions for 24 groups of up to 10 children involving interactive games with a PeopleBot™ robot. The second study involved individual human participants interacting with the PeopleBot™ robot in simulated living room task based scenarios. Prior to both these two studies, the initial social space and comfort distance experimental observations and measurements were carried relevant to this study. The third study was conducted in non-laboratory relatively uncontrolled conditions as part of a demonstration HRI trial event as part of an evenings entertainment in a reception type situation for delegates who attended the 2005 Artificial Intelligence Society of Britain (AISB) Symposium which was hosted by the University of Hertfordshire.

3.2 HR Initial Proximity Experiment (IPE).

The VICTEC (Virtual Information and Computing Technology with Empathic Characters) project ran from March 2002 to Jan 2005 and investigated how virtual drama, emergent narrative and empathic characters might be used in personal and social education or schoolchildren, in particular for education against bullying. For the VICTEC project, about 400 school children (all but two were born and raised in the U.K., all aged between 9 and 11 year and chosen from 10 schools in the Hertfordshire area) visited UH and 194 of these participated in the experimental HRI sessions described here. These sessions were used to run 24 interactive game sessions with groups of children interacting with a single robot. The main aims were to investigate interaction styles in a group scenario involving the children. An Initial Proximity Experiment (IPE) was conducted before the children had participated in the interactive games, before any other interaction took place and the children had actually seen the robot move. The robot was stationary, though powered up and activated. Therefore, noises from the sonar range sensors and motors were audible throughout the game area.

3.2.1 IPE Method and Procedure

The PeopleBot™ robots were fitted with a lifting arm with a pink hand, and a small white basket fitted which was used to hold small presents (Figure 13). The arm could be raised or lowered under program control. The IPE experiment was performed in an enclosed area of 6m x 6m which was marked out from the centre with a series of concentric circles at 0.5m radii intervals. The robot was positioned initially at the centre of the circles, so an observer was able to use these to estimate the initial distance and relative orientation of members of each group; either directly or from the video recording of the session. The robots were controlled in a semi-autonomous manner by WoZ operators who were hidden in an adjoining third room along with necessary recording and communication equipment.

Figure 14: A group of children take up their positions relative to the robot on their first encounter.

The sessions were coordinated by an experimenter and followed the overall format outlined here:

1. The children entered the room and each child was given a numbered sticker that was attached to their clothing so that the children could be tracked through the experiment.

2. An initial opinion questionnaire was administered before the children saw the robot and also asked for their genders and tracking numbers.

3. The robot was then uncovered and the experimenter let the children move around the robot without giving them any indication of where they should position themselves (Figure 14). Once settled, usually after a period of approximately 1 minute, each child's relative position and orientation towards the robot was recorded on paper record charts (Figure 15) by an assistant to the experiment supervisor. The initial distances were estimated to the nearest 0.5m circle marking on the floor, giving an

accuracy of ±0.25m. Also recorded was whether a teacher was present at the session, along with any other notable or relevant observations.

4. Two interactive games were then played before a final questionnaire was administered. (These latter parts of the session were separate experiments and are not considered here. See te Boekhorst et al. (2006) and Woods et al. (2005) for more details of these other parts of the sessions).

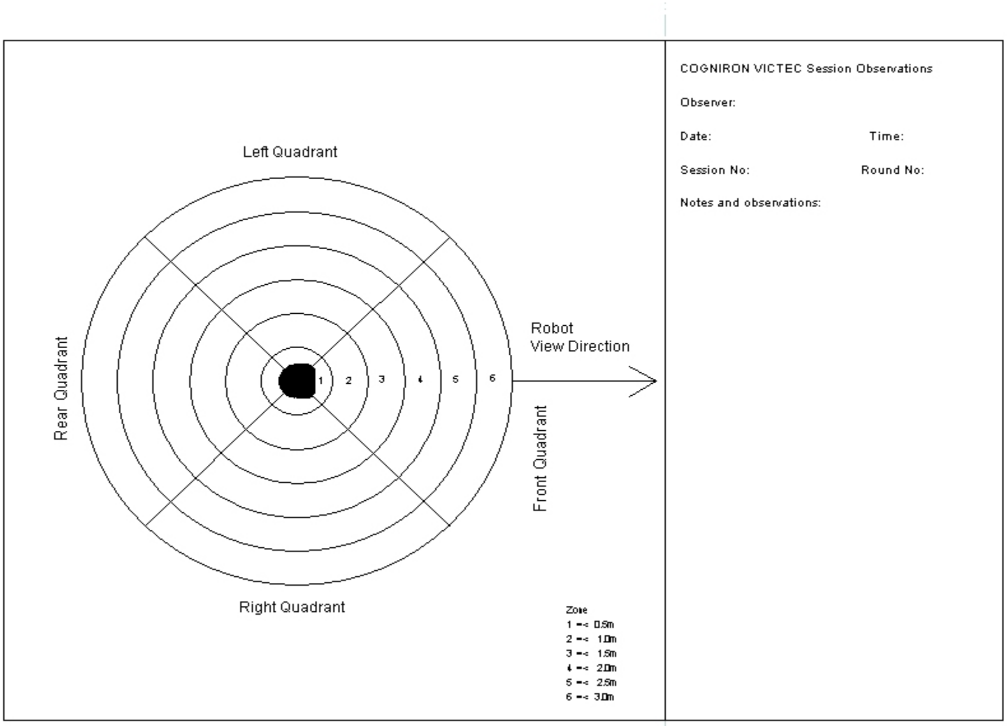


Figure 15: The paper record chart used to record children's initial positions and orientations relative to the robot for each session

The position and orientation measurements were later checked and verified against video recordings of the sessions. The PeopleBot™ robot had a mechanoid appearance, so only the following visual cues indicated the front of the robot:

1. The direction which the robot moved, either forwards or reverse, gave an indication of possible front and rear ends of the robot. This was not apparent until the robot moved, which had not occurred at this stage of the test. Therefore, it would not be a factor to consider in this part of the study.

2. A camera was mounted on top and to the front edge of the robot and pointed forward when the robot was activated, but was stationary for the duration of this experiment.

3. The PeopleBots™ used in the experiment were fitted with a simple lifting arm on the right hand side. It was in its lowered position at this stage of the experiment. On the left hand side the robots were fitted with a basket (empty at this stage) to hold presents which would be given during the course of the later game experiment. The arm did not move for the duration of the IPE.

3.2.2 IPE Findings

From the total sample of 194 children, only 131 (71 boys and 60 girls) were included in the analysis. A General Linear Model (GLM) Univariate Analysis of Variance (UANOVA) test showed that there was a significant effect on mean approach distances when the class teacher was present ($F = 8.747$, $p < 0.001$). After observation of the video recordings of the experiment sessions it became apparent that some of the groups of children had been told explicitly where to stand initially, or were not given the opportunity to take up their initial positions by a teacher or adult present. Results from these particular groups were therefore excluded from the analysis and the teacher present effect disappeared. The initial distance results are summarised in Table 4 and in Figure 16.

Table 4: Closest Approach Distance by Children's Gender

Dependent Variable: Closest Approach Distance				
Gender	**Mean (m)**	**Std. Error**	**95% Confidence Interval**	
			Lower Bound	*Upper Bound*
Male	1.823	.082	1.661	1.985
Female	1.880	.092	1.698	2.062
All	1.852	.062	1.730	1.973

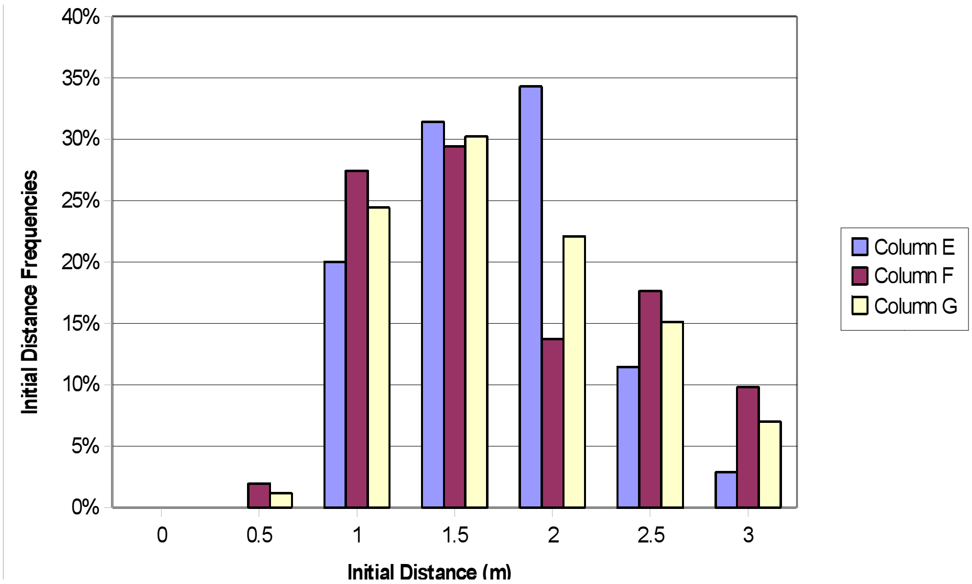


Figure 16: Children's initial distances relative to robot (front orientation only) for boys, girls and all children

GLM UNANOVA tests revealed no significant differences between the mean approach distances for gender (F= 0.169, p = 0.681), though there was an effect for approach direction (F = 0.3473, p = 0.022). The children who positioned themselves behind the robot tended to keep further distances from the robot than those who orientated themselves towards the front or side. Overall, the children tended to place themselves at an overall mean distance of 1.85m, which is consistent with the Hall's Personal social spatial zone distance and would normally be used by humans to communicate with non-friends. Note; Hall's Personal Spatial Zone ranges from approximately 1.2m to 3.6m.

The implication is that most of the children respected the robot's personal space and thus can be considered to have related to the robot as a social entity, even though the PeopleBot™ robots used for the study were mechanoid in appearance and only had one arm (which was the only explicit anthropomorphic feature). However, there are other possible explanations for the children's apparent social behaviour towards the robot: The robot's on-board video camera may have acted as a focus of the children's attention, the children may have been eager to interact due to the play context or, because of the detailed preparation and school excursion necessary for the event to take place, they may have been primed to expect an interaction with the robot.

The initial orientation of each child was estimated by which quarter each child was initially positioned in relative to the robot, and recorded as front, right, left or back. The results are summarized in Tables 5 and 6. The initial distance and orientation results presented here suggest that there is a strong tendency for a majority of just over half of the children (53%) to position themselves to the front of the robot initially. There was also an indication that slightly more boys than girls (59% to 47%) positioned themselves at the front of the robot.

Table 5: Children's Initial Orientations Relative to the Robot

Children in front of robot	70 (53.%)
Children to right of robot	27 (21.%)
Children to left of robot	16 (13%)
Children behind robot	16 (13%)

Table 6: Closest Approach Distances by Children's Orientations

Dependent Variable = Closest Approach Distance				
Orientation to Robot (F, R, L, B)	**Mean (m)**	**Std. Error**	**95% Confidence Interval**	
			Lower Bound	*Upper Bound*
Front	1.722	.069	1.586	1.858
Right	1.842	.113	1.369	2.066
Left	1.769	.144	1.485	2.054
Behind	2.073	.150	1.777	2.369

There were significant differences for the children's initial orientations towards the robot ($\chi 2$ = 111.187, $p < 0.001$) . From from the number of children who positioned themselves at the front of the robot (53%), it could be inferred that the camera or the pointer (or both together) are powerful attractors of the children's initial attention, even though the camera, arm and robot were stationary (Table 5). There may also be a weaker indication that the stationary arm pointer possibly had some effect in causing some children to prefer positions on the robot's right side (21%) as opposed to left side (13%) or behind the robot (13%). However, the entrance to the game area was to the right of the robot so this may possibly have affected this observed right-left preference. It was noted that any further experiments should control for this as well as for the initial orientation of the robot.

3.3 Comfortable Approach Distance Experiment (CADE)

The second exploratory HRI proxemic experimental study took place as the initial part of a larger series of controlled HRI trials. This second study was also an exploratory investigation and involved twenty-eight sessions with individual adults interacting with a single robot in simulated living room scenarios. For this experiment, the robot's hand was not as anthropomorphic in appearance as that used for the previous IPE study as the arm was adapted so that it could pick up and carry small palettes, which contained items to be brought to the human participant later on in the task scenarios (Figure 17).

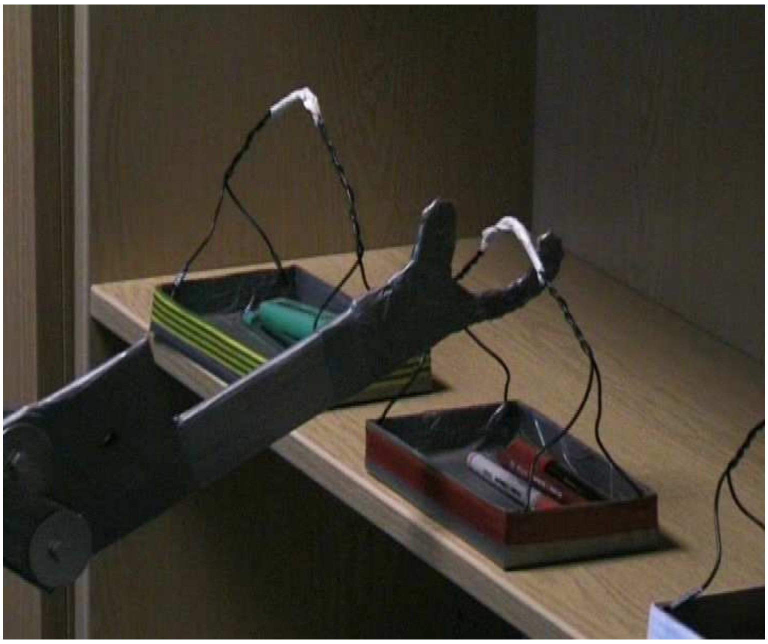


Figure 17: Detail showing the robot's arm and hand used in the study with adult participants

A large conference room (9m x 5m) was converted and furnished to provide as homely an environment as possible. Adjacent was an enclosed section where the WoZ robot operators and equipment were housed. The participant sample set consisted of 28 adult volunteers [male: N: 14 (50%) and female: N: 14 (50%)] recruited from the University. A small proportion (7%) was under 25 years of age, but no one younger than 18 took part. Approximately 43% were 26-35 years old, 29% 36-45 years old, 11% 46-55 years old and 11% were over 56 years of age. 39% of the participants were students, 43% academic or faculty staff (e.g. lecturers, professors) and 18% were researchers in an academic institution. Approximately 50% came from a robotics or technology-related department (e.g. computer science, electronics and engineering), and 50% came from a non-technology related department, such as psychology, law or business. All participants completed consent forms and were not paid for participation, but at the end of the trial they were given a book as a present.

3.3.1 CADE Method and Procedure

Initial HR distance measurements were conducted before separate experimental sessions involving human-robot interactions in task based scenarios. Scale marks were made on the floor at 0.5m intervals along the diagonal of the room (Figures 18 and 19) and the human-robot comfort and approach distances were estimated from the video records, after the trials were completed, rather than making intrusive measurements or notes during the sessions. The interpersonal measurements were made from the closest part of the participants feet (invariably the front of the leading foot, shoe or toe) to the nearest part of the lower bump ring on the robot. This provided measurements of interpersonal distances which were close approximations (estimated at better than ±2.5cm) to the standard HR distances as measured between closest body part to body part (cf. Chapter 2.5).

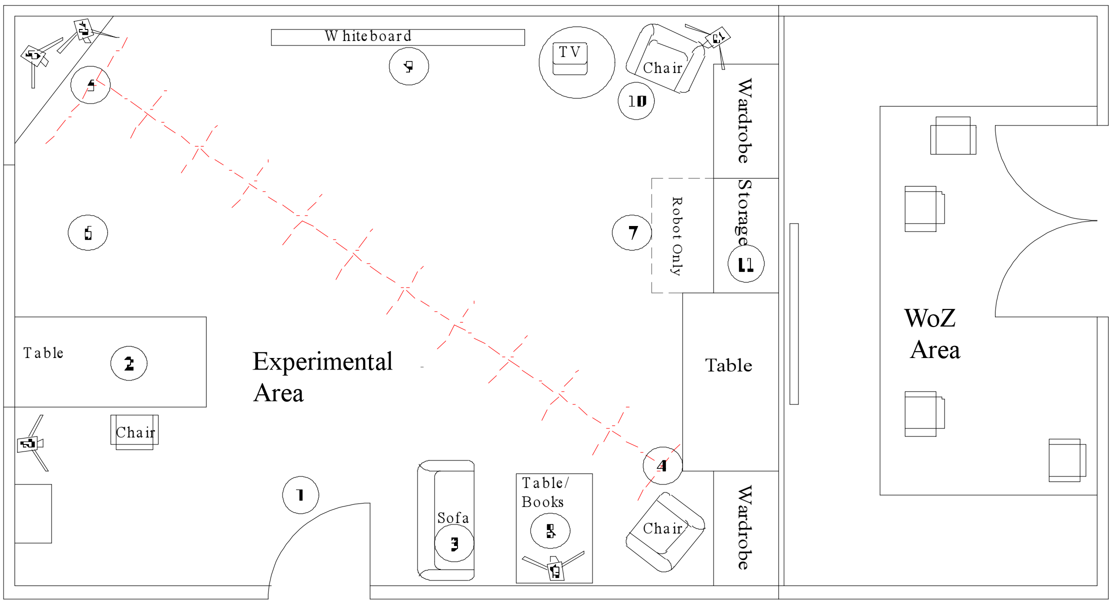


Figure 18: Plan view of simulated living room layout. Comfort distance tests carried were out along the marked diagonal line.

Each experiment session followed the same format:

1. Entry to room and introduction of robot

2. Co-habituation and initial questionnaires. While the participant was completing the questionnaires, the robot wandered randomly around the test area. Unlike the previous IPE study, each participant was allowed to acclimatize to the robot for five to ten minutes prior to the distance tests.

3. Comfort and social distance tests.

4. Various other HRI experimental task scenarios and questionnaires. These latter parts were carried out for separate HRI investigations and are therefore not considered here. More details can be found in Dautenhahn et al. (2005), Koay et al. (2005), Koay et al. (2006), Walters et al. (2005b), Walters et al. (2005c), Woods et al. (2005) and Woods et al. (2005a).

Figure 19: Views of the Simulated living room showing the robot and the 0.5m scale marked diagonally on the floor

The experiments were supervised by an experimenter who introduced and explained the tests to be carried out to the participant. Otherwise, she interfered as little as possible with the actual experiment. For measuring the human participant's comfortable distance when approaching the robot, the robot was driven to point 5 (next to the corner table) and turned to face along the distance scale towards point 4 (Figures 18 and 19). The participant was told to start at point 4 and to move towards the robot until he or she felt that they were at a comfortable distance away from the robot. Next, they were told to move as close to the robot as they physically could, then to move away again to a comfortable distance. They were then told to repeat these steps once again as a consistency check. The comfortable approach, closest physical and comfortable withdrawal distances were measured for each of the two tests to the nearest 0.25m (accuracy ±0.125m) by later close observation of the video records. The next part of the comfort distance tests was to measure the participant's comfort distance with the robot moving from point 5 towards the participant. The participant was told to stand at point 4, and the robot moved directly towards him or her. The participant was told to say, "Stop", when the robot was as close as the participant desired. The distance of the robot when the participant said, "stop" was estimated later, and recorded, from close observation of the video records.

3.3.2 CADE Findings

Overall, the mean Human to Robot (HR) comfortable approach distances was found to be 71cm and for the Robot to Human (RH) approaches slightly greater at 88cm. A Pearson test indicated that participants mean HR and RH approach distances were correlated (r = 0.419, p = 0.26). Some distortion of the figures has probably occurred because of the threshold effect on the robot to human approach distances due to the object avoidance behaviour of the robot preventing approaches closer than 0.5m.

The means of the four robot comfortable approach distance results obtained were calculated for each participant and a histogram was plotted with the ranges set at 0.25m intervals. The results are presented in the charts in Figure 20 and 21.

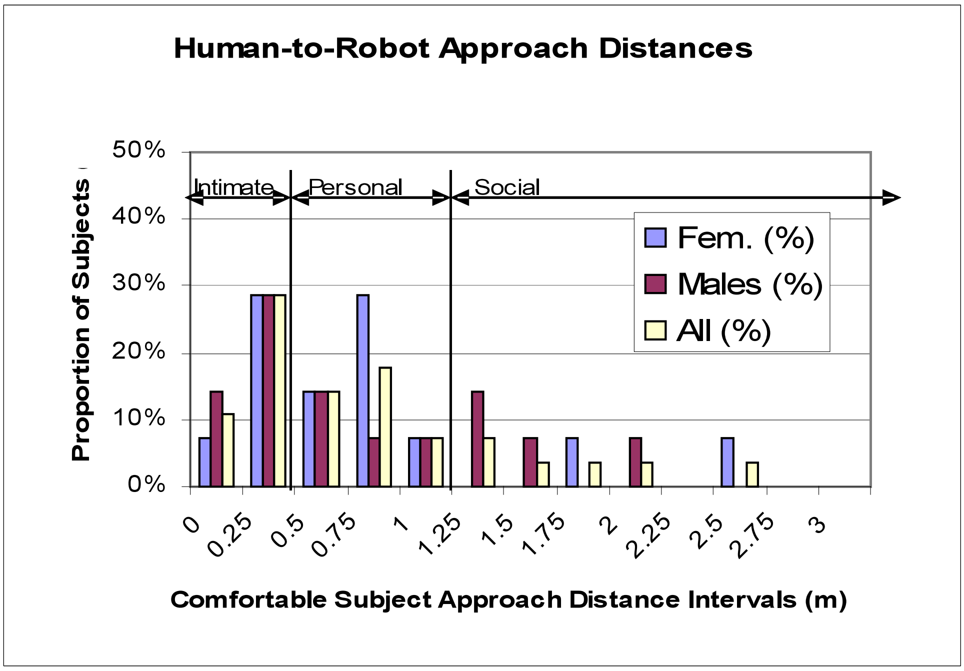


Figure 20: Comfortable approach distance frequencies for participants ***approaching*** *the robot.*

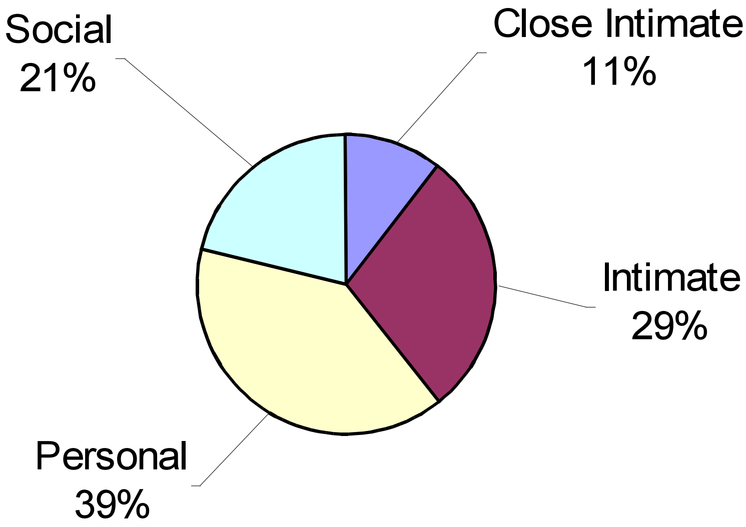


Figure 21: Hall's Spatial Zone Categories for Robot to Human Approach Distances Results

Approximately 40% of participants approached the robot to a distance of 0.5m or less. When the robot approached a human, the anti-collision safety system prevented it moving closer than 0.5m. Due to safety concerns this system had to be kept operational for the duration of the trials. It can also be seen that approximately 40% of the participants also allowed the robot to approach right up to this 0.5m limit (Figure 22) . That they did not stop the robot from physically approaching so closely to them indicates that the robot did not make them feel threatened or uncomfortable. When asked later if they felt uncomfortable while standing in front of the robot most participants (82%) indicated that they were not uncomfortable. Also, as less than 20% indicated that they wanted a robot for a friend or companion, these close approach distances did not express the participants' wish to be intimate with the robot. That many of the participants approached the robot closely, and tolerated a relatively close approach implied that they might not see the robot as a social entity in the same way that they would perceive another human (cf. Hall (1968)). Interestingly, there were a small number of participants (approximately 10%) who were uncomfortable in letting the robot approach closer than the far end of the social zone (>1.2m and <3.6m), which is usually reserved for conversations between humans who are strangers to each other.

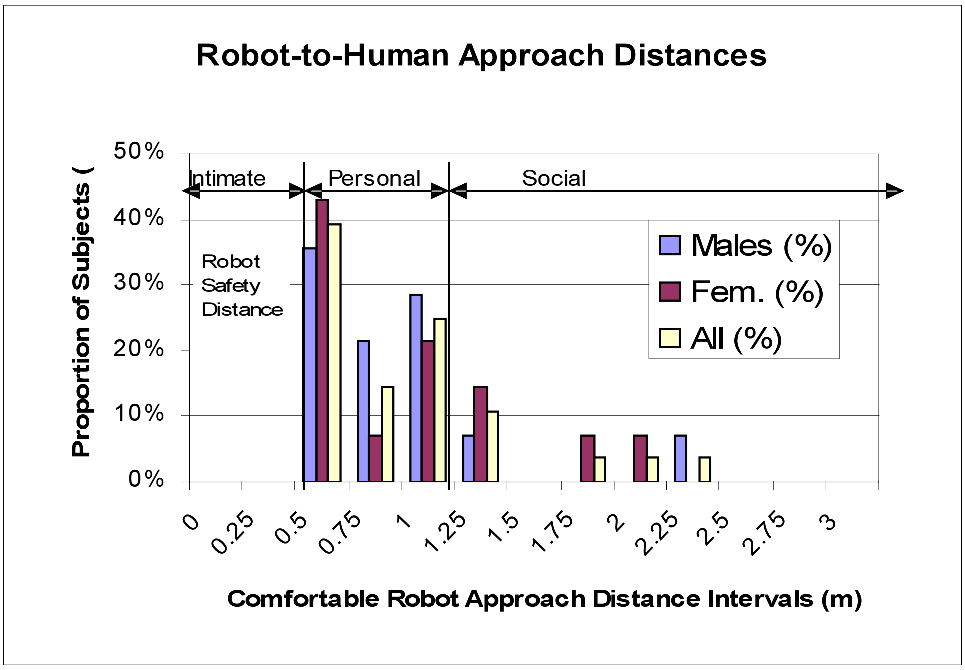


Figure 22: Comfortable stopping distances for the ***robot approaching the participants***

3.4 Proximity and Robot Voice Experiment (PRVE)

A third exploratory study, the HR Proximity and Robot Voice Experiment (PRVE), which included the additional factor of robot voice styles on peoples comfortable approach distances and was performed as one of two demonstration HRI trial events at the 2005 AISB Symposium at the University of Hertfordshire during April 2005. Results from the other demonstration trial, which investigated robot approach directions to a seated person, can be found in Woods et al. (2006a) and Walters et al. (2006). The experience gained from the previous IPE and CADE trials had led to some improvements in the experimental procedure, but this experiment was essentially the same as the previous CADE exploratory study. The enhancements for the trial procedure and methodology included better resolution for the distance measurements, and also included four different robot voice style conditions. This was to investigate the effect of robot voice style on HR comfortable approach distances.

3.4.1 PRVE Method and Procedure

The PeopleBot™ robot was set up in the far corner of an area which was enclosed on three sides by screens and an outside wall with a window covered by a blind. The robot also incorporated the simple one DoF lifting arm with a fixed hook style finger, as used for the simple gestures and manipulations in the previous single adult approach distance trials. Therefore it was left in place for consistency (see Figure 17). The participants were all attendees and presenters at the AISB 2005 Symposium at the University of Hertfordshire, and the session was run over two hours as one of several demonstrations of HRI Trials and Robotics research which was currently taking place by members of the Adaptive Systems Research Group based at the University. Over the course of the two hour session, 21 (36%) females and 37 (64%) males (58 total) volunteered to participate in the Human-Robot (HR) social distance experiment. Most participants (approximately 83%) described themselves as being familiar with robots and computer technology and all described themselves as academics or scientists. 36 (62%) had previously participated in the other separate HRI experiment which had involved a PeopleBot™ robot approaching them from different directions while seated in an armchair. The participants were classified by age into three groups: 29 and under (32%), 30 to 39 (30%) and 40 and over (38%). All were right handed apart from 4 males who listed themselves as either left handed (2) or ambidextrous (2).

Participants of this PRVE signed consent forms and provided basic demographic details, including age, gender, handedness and working background and experience by means of a short questionnaire. They then entered the experimental area. The robot was situated in the far corner of the area, switched on and making various noises from servos, sonar and cooling fans. In the trial conditions where the robot was to have a voice (male, female or synthesized), the robot gave instructions to the participant in the appropriate voice. The four robot voices style conditions were:

1. Male Voice - The voice was a high quality male voice which was recorded using a male human speaker with a neutral English accent.

2. Female Voice - This voice was a high quality female voice recorded using a female human speaker with a neutral English accent.

3. Synthesized Voice - This was a relatively low quality voice which was created using a text to speech synthesizer (Festival Lite V2 - "flite", Open Source speech synthesis software from CMU). The voice was obviously synthesized, and was a male voice, pitched high in order to achieve an androgynous voice style, with a slight American English accent

4. No Voice - The male experimenter read the instructions from the script. The accent used was a neutral UK English.

In all cases the script for the instructions was identical, apart from the part indicated in bold below for the no voice condition where the experimenter gave the instructions:

1. "Welcome to the second part of our demonstration. We are investigating how robots should behave in the presence of people and we would be grateful if you would participate in a short experiment."

2. "If you are uncomfortable with this, or do not wish to participate for any reason, you may leave through the exit to the side of the test area."

   Note: If the participants exited the test area at this point (or did not want to continue at any point) this would have terminated the exchange.

3. "Thank you. We are very pleased that you have agreed to help by participating in this experiment. We want to find out the distance that humans prefer to take relative to robots."

4. “When I say ‘Approach now’, would you approach **me** (if spoken by the robot, or for the no voice condition the supervisor says “**the robot**” as appropriate) to a distance which you feel is the most comfortable for you. When you reach that distance, please raise your hand.”

   If the participant did not understand, the last instruction was repeated. Otherwise:

5. “Approach now”

   Once the participant had approached the robot to their desired comfortable distance and raised their hand the experiment supervisor then measured that approach distance.

6. “Thank you for participating in our experiment. Please continue on through the area exit”.

   The participant exited the test area.

In order to find out more about participants’ perception of the robot (as linked to the male and female voices), at the very end of each trial each participant was asked to provide a name for the robot. Distance measurements were made using a marked paper tape strip on the floor and a tape measure, similar to Stratton et al. (1973). To standardize and to be able to compare the measurements with those from previous proxemic experiments (cf. sections 3.1 and 3.2), they were again made from the closest (front) part of the participants feet to the nearest part of the lower bump ring on the robot (cf. Chapter 2.2). However, the accuracy was better than for the previous experiments and measurements were made to the nearest whole cm (accuracy ± 0.5cm).

3.4.2 PRVE Findings

A GLM UANOVA for group factors was performed on the approach distance data and significant differences were only found in the approach distances means when participants were grouped by the robot voice used and also whether they had participated in the approach distance trial only or had also previously taken part in the other demonstration HRI trial. The significant findings are presented and discussed in detail below:

3.4.2.1 Robot Voice

The overall distribution of the measured approach distances is shown in Figure 23. Comparing the overall approach distances to Hall's social distances, approximately 33% of the participants approached to a distance comparable to the Intimate zone, 56% to the Personal zone and 12% to the Social zone (N = 58).

A similar proportion of close (intimate zone) approaches were observed in the CADE study with robot naive adults encountering the same robot for the first time (cf. Walters et al. (2005a)). Consistent with this previous study, there was also a small proportion of participants who took up approach distances that were close to the far limit for the social zone. In fact, one person took up a position that was as far from the robot as the test area would allow. There were significant differences between approach distances for the the group approaching the robot with the synthesized voice (n= 15, mean 80.3cm) and the groups approaching the robot with a male voice (n = 10, mean 51.5cm, p = 0.030), female voice (n = 19; mean = 60.3cm, p = 0.048) and no voice conditions (n = 14, mean 42.4cm, p= 0.002) (Figure 24).

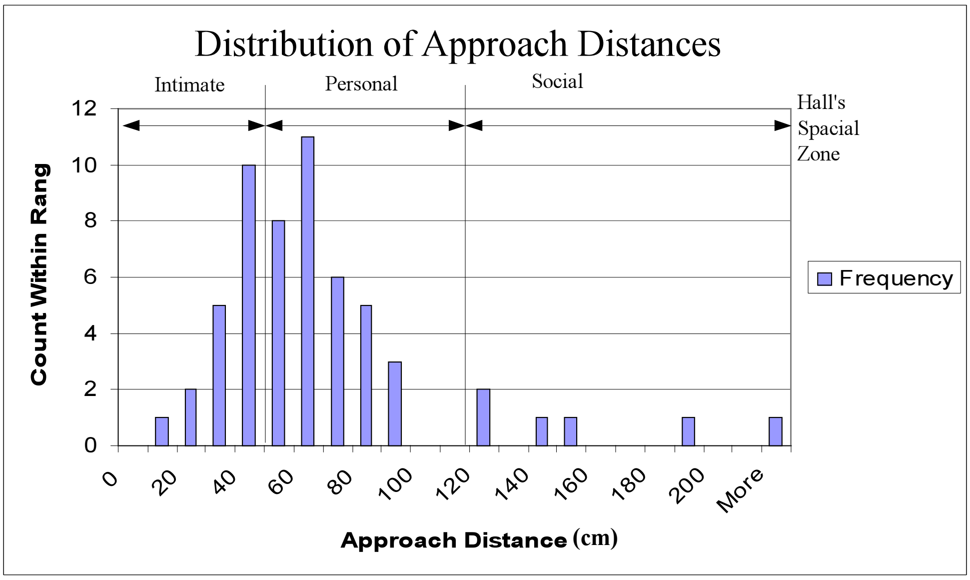


Figure 23: Overall distribution of HR approach distances (cms) for all robot voice style conditions.

It can be seen that the mean approach distance to the robot with a synthesized voice is greater than the other three robot voice conditions and (according to Hall's social spatial zone distances) nearest to that which would be expected from a comparable human-human proxemic situation. The mean approach distances to the robot with the other voice conditions are generally closer than humans would position themselves to each other on first acquaintance (if interpreted in line with Hall's spatial zone theory).

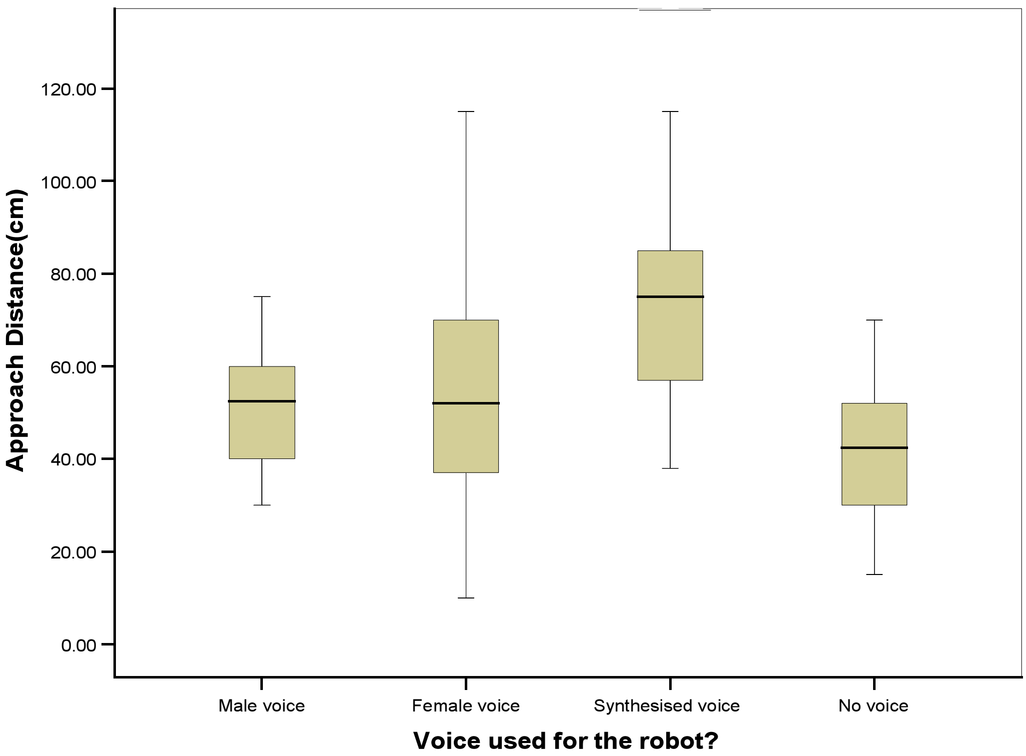


Figure 24: HR Approach Distances Box Plot for Robot Voice Style

3.4.2.2 Previous Trial Experience

There were significant differences in the HR approach distances displayed by participants who had earlier that same evening participated in a a separate HRI demonstration trial as part of the same event. This previous trial consisted of an identical PeopleBot™ approaching the seated participant from three different directions. The results from this previous trial are documented more fully in Woods et al. (2006) and Walters et al. (2006) and more details are incidentally provided in in Chapter 4. The participants who had previously experienced an interaction with a PeopleBot™ approached the robot significantly closer ($n = 36$, mean 51.2cm, $p = 0.017$) than those for whom this was their first encounter ($n = 22$, mean 73.9cm, $p = 0.017$). Figure 24 illustrates that this difference is mainly apparent for the robots with synthesised and female voices.

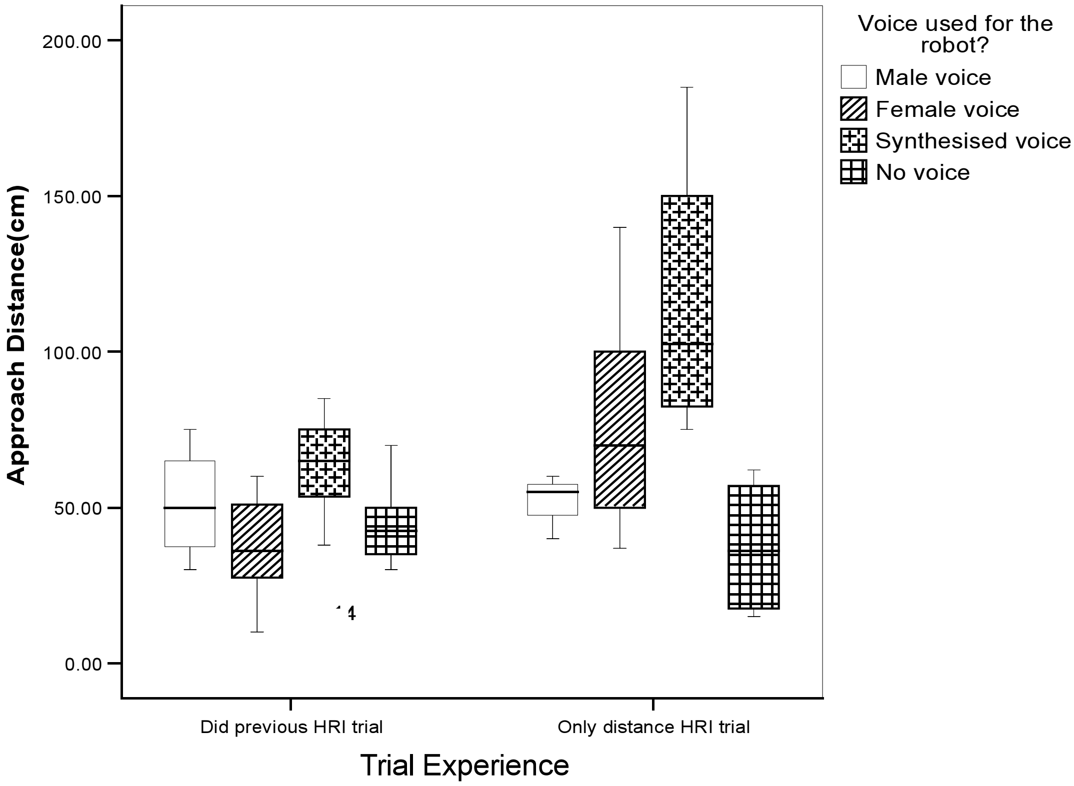


Figure 25: HR Approach Distances for the Robot Voice Styles, Grouped by Previous Trial Exposure to the PeopleBot™ Robot

3.4.2.3 Robot Names and Robot Gender

As a final item for the RVE trial, each participant was asked to provide a name for the robot. These names were sorted into three groups depending on the perceived gender of the names: Male, Female and Neutral. Of the 32 participants who supplied a name for the robot, 16 (50%) provided a Male name, 15 (48%) a Neutral name and only 1 (2%) a Female name. Interestingly, no one actually gave the robot with the high quality (recorded) female voice style a female name; the sole female robot name being given to the robot with the synthesized voice.

At a later demonstration event at the Science Museum in London in 2005 (cf. Chapter 2.3) the same PeopleBotTM robot performed interactive games with children (ages estimated to range from 4 to 10 years) who were then asked to provide a name for the robot. The names obtained were grouped similarly and the results were: Male names 50 (41%), Neutral names 66 (58%) and only 2 (1%) gave the robot a Female name. It is interesting to note that while these two results have been gained in a relatively uncontrolled public HRI environment, it does provide evidence that a large majority of people (including children and academics) certainly do not perceive the PeopleBot™ robot as female and tend to see it as either male or of indeterminate gender.

3.5 Discussion of Exploratory Investigations into Human-Robot Social Spaces

These initial exploratory HRI studies which performed basic measurements of the distances people keep, both when when approaching and being approached by a mechanoid robot has raised many issues. While the experimental set-ups of the first two HRI experimental studies presented in this chapter were very different from each other, comparisons between the spatial zones measurements obtained can highlight results which may generalize across the different experimental set-ups. In all three experiments presented in this chapter, majorities for both children and adult participants took up an initial approach positions relative to the robot which were consistent with Hall's human-human social space zones. A major difference between the first exploratory HR social distance studies and the second study was that the children interacted with the robot in groups, whereas in the latter two studies the adults interacted individually with a robot. It is very likely that the children took cues from, and were interacting with each other as well as the robot (cf. for a discussion of social facilitation effects with regard to this trial in Woods et al. (2005)). Also, the children would also have respected each others personal spaces, so this may well have affected the initial distances they may have taken with respect to the robot. Most children generally took up distances from the robot which where compatible with Hall's Social spatial zone distance (1.2 to 3.5m) which would amongst humans be reserved for talking or interacting with strangers or other non-friends. However, most adults took up Hall spatial zone distances which (in a human-human context) would be used for talking with close friends. Generally, these results support the initial research hypothesis, namely that distances used in direct human-human social interaction can apply to robots and that people respect robots interpersonal spaces. This could however simply be a convenient distance for viewing the robot, so more tests are required to confirm the reasons for these observations. A small proportion (<10%) of each group took up an initial distance as far from the robot as the limited space allowed.

Interestingly, for the adult participants of both the CADE and PRVE trials, which included both robot experienced and robot naive participants, there was a sizeable minority (up to 40%) who took up an initial approach positions relative to the robot which were so close that they were within Hall's intimate spatial zone, reserved for very close friends or lovers. This was observed across both individual adult trials, and if interpreted only in terms of Hall's social spatial zones theory, may indicate that this proportion of participants did not perceive the robot in a social way.

The adult studies did not consider the initial orientation of the participants to the robot, due to the lack of space in the experimental rooms, but the children’s study did gain results that indicated that the only two possible anthropomorphic features which distinguished the front and back of the robot, the hand/arm and the camera, did probably exert an effect on where the children chose to orientate themselves when initially encountering the robot. There are also some indications that the arm and hand may also exert a right hand bias to the children’s initial orientations, though this needs further study to confirm as the entry to the game arena was also to the right of where the robot was positioned initially.

For the PRVE study the overall mean approach distance to the robot with a synthesized voice was significantly greater then the other three robot voice conditions and nearest to that which would be expected from a comparable human-human proxemic situation, according to a strict interpretation of Hall's spatial zones. According to this interpretation, the mean approach distances to the robot with the other voice conditions are also generally closer than humans would position themselves to each other on first acquaintance. These results are consistent with results obtained from the two previous comfortable approach distance experiments where humans approached robots considered here (cf. Walters et al. (2005a) & Walters et al. (2006)). Over all these HRI proxemic trials, approximately 90% of the participants approached the mechanical looking (PeopleBot™) robot to distances ranging from 40cm to 100cm (Mean 71cm, St. Dev. 63.0). However, Nakauchi & Simmons (2002) performed experiments measuring personal space distances for humans standing in a queue or line (with each person facing the back of the previous person) and found that the experimentally derived distances were from just less than 40cm to 80cm. Comparing these actual experimental results to Hall's social space zone distances, they seem to suggest that (non-interacting) humans in a line and humans approaching robots both take up approach distances that (according to Hall) are reserved for communications between friends. Indeed, substantial proportions (nearly 40% of participants in our previous trials) approach the robot to close to the upper limit of the *intimate* zone, reserved for very close friends and family! To account for these observed distances in terms of Hall's social spatial zones theory, one must assume either that the robots are being treated like a close (even intimate!) friend (a very unlikely explanation which contradicts results from our previous study into people's perceptions of the PeopleBot™ robots (cf. Dautenhahn et al. (2005)). The other possible explanation is that this proportion of humans perceives the robot more as they would an inanimate object. This latter explanation is lent some credence by Sommer (1969), who suggests that when humans are forced (e.g. by physical circumstance etc.) to be closer than they would prefer, they effectively "de-humanise" people who are invading their personal space bubble and treat them as inanimate objects, to which they can then approach arbitrarily closely. However, in both the HR approach experiments performed for this study and in Nakauchi and Simmons's experiments with people in queues, the participants were free to take up as large or small a distance as they felt was comfortable.

In Chapter 2, human-human proxemic behaviour was considered in more depth. In the light of these review results, it can be seen that Hall's original broad categories of social spaces have been shown to be affected greatly by a number of additional factors which allows me to propose a different interpretation of these results. Hall's original research into human-human social spaces were mainly qualitative and his spatial zones were originally proposed to indicate broad cultural proxemic differences. His social zone distances were estimated (for

North Americans) in terms of body, arm contact or reaching distances. The actual quantitative measures given in Chapter 2 Table 1, are actually later estimates (cf. Lambert (2004)) derived from Hall's original definitions. Other subsequent studies which tried to quantify the effects of human social spaces found that humans tended to approach each other to comfortable distances that were greater than those for an inanimate object of similar size. Stratton et al. (1973) performed human-human approach trials where participants approached other humans and reported "comfortable" mean approach distances ranging from 13.9 to 27 inches (35 to 69 cm).

These distances are comparable to those obtained by Nakauchi and Simmons, and also to those obtained from both the CADE and PRVE findings presented here, where participants approached the robot to comfortable approach distances. Indeed, the initial approaches for the robots with the female and synthesized voices in the PRVE study are actually slightly greater than would be expected for the comparable human-human case. This difference was not apparent in those who had encountered the PeopleBot™ in the previous trial. A possible explanation of this result is that as most people perceived all the robots as male or neutral at first encounter, when the robot actually spoke with a female or synthesized voice, this did not meet their initial expectations of the robot. Thus they may therefore have reacted with a slightly wary approach to these robots, proportional to the perceived "threat". Of course the threat posed by these robots was not very great, so the "flight" response is noticeable as a slightly greater approach distance. In the light of these more detailed human-human psychological findings, it can be can be seen therefore that overall, the human approach distances to the robots for both the adult studies is actually well within the range of distances which would be considered normal for human-human approaches.

In the third PRVE study, the participants who had *not* experienced an HRI trial previously, actually approached the robots with male and no voices to distances that would be considered normal in the human-human case. However, they approached the robots with synthesized and female voices to distances that were slightly greater than would be expected from a comparable human-human interaction context and situation, but was comparable to the effect observed by Stratton et al. (1973) who speculated that slightly greater observed approach distances to the headless tailors dummy in their trials were due to the (in this case, slight) "fear of the strange" effect, comparable to that which Hebb (1958) had found in non-human primates and possibly related to the "uncanny valley" effect noted by Mori (1970) (cf. Chapter 2 for a discussion of this effect and possible biological origins). The “uncanny valley” repulsive effect has been reported by MacDorman (2006) and others, as applying to androids robots and there is evidence that the repulsive effect can apply to mechanoid robots (cf. Bethal & Murphy (2006) and Hanson et al. (2005)) and also to humanoid robots. The repulsive effect tends to be large for small perceived inconsistencies and minor for relatively large inconsistencies.

For both the IPE study and the CADE study, the social distance experiments were performed before any other interactions had taken place. With more opportunity for habituation, the perception of the participants may have changed over the course of the experiments. The evidence from the PRVE study suggests that even after a very short period of habituation, of the order of a 5 or 10 minutes only, participants tended to approach the robot more closely. The participants seem therefore to have judged the robots initially very quickly, perhaps based mainly on its appearance (cf. Lee & Keisler (2005)). It was therefore concluded that it would be desirable for future experiments to perform distance experiments both before and after exposure to robot scenarios to see how participants’ perceptions change with both short and longer term exposures to robots. There was also a need to perform long-term studies (over periods of longer than one hour) and repeated exposures of the participants to the robot over longer periods of time.(cf. Chapter 6 for more details of a longitudinal HRI study)

We (cf. te Boekhorst et al. (2006) and Walters et al. (2006), Walters et al. (2007d)) and many others, including Goetz et al. (2003), Hinds et al. (2004), Kanda et al. (2007) and MacDorman (2005) have found that consistency of robot appearance and behaviour is important in gaining a positive or believable perception of robots and their capabilities by humans. Nomura et al. (2007) have found that participant's anxiety towards a (small humanoid) robot has a significant effect on the distance they will allow the robot to approach. Therefore, the perceived inconsistency (with regard to the synthesized and female robot voice styles) may have caused them to react with a slight anxiety, causing an initial reluctance to approach. This reluctance disappeared once they had refined and changed their initial perception of a particular robot after a relatively short period of actual interaction; in this case after only a few minutes of habituation. Nass et al. (1994) and Reeves & Nass (1996) have shown that computers and technological artefacts elicit a range of social responses from humans. However, humans do not respect the interpersonal space of computers, otherwise they would be unusable! The findings from this study have shown that humans do respect the personal spaces of even stationary mechanoid robots. This is almost certainly due to their physical form and embodiment.

What humans actually perceive and rate as consistency in robot appearance and behaviour, and how these relate to the functionality, perception and effectiveness of robots, are currently open questions in the field of HRI research. The appearance of the robot in these three exploratory HRI proximity trials was mechanoid. It was concluded that future work for the study should also investigate the effect of robot appearance on human to robot approach distances, and also how this may change with longer term exposures and differing robot appearances. In humans, proximity is affected by environmental factors (size of room, corridor etc.) and the nature of the interaction. In robots, the nature of the interaction is limited compared to the myriad ways in which humans can interact, but it is likely that there will be proxemic effects related to the limited robot nature of the interaction. In this study, the *context* of an interaction is the term used for the robots perception of the nature of the (task) interaction. The *situation* is the term for the robots perception of the environment (including the orientation, posture and position of any humans) in which the HRI takes place (cf. Chapter 1). Some of these issues are addressed in our other recent studies (cf. Walters et al. (2007d), Syrdal et al. (2007a) & Koay et al. (2007b)) and those specifically related to this study in the following Chapters.

In all three exploratory HR proximity trials, it was apparent that a small proportion of participants (10% or less) took up initial positions relative to the robot which were almost as far from the robot as the experimental space allowed. In the IPE study, where orientation towards the robot was recorded along with the initial distances, these far approaches tended to be correlated with those children who also placed themselves behind the robot. In human-

human proxemic situations, behaviour such as this might indicate a desire not to be noticed by the robot. It seems therefore, that for the children who did not approach closely to the robot, it was because they were nervous or uncertain of the robot.

In the case of the adults who took up similarly far approach distances, it is probable that some of the far approaches were also because of nervousness with regard to the robot on the part of particular participants. However, especially in the case of the third PRVE study, which was performed with mostly robot experienced participants, it is conceivable that the far approaches may be due to another interpretation. Humans can use social distance to "reward" or "punish" each other (cf . Burgoon & Jones (1976) and Chapter 2). Some of those those who took up an untypically far approach distance from the robot could also be interpreted as "punishing" the robot. In other words, they may be expressing disapproval towards the robot. From the robot's point of view, it probably needs to exercise special care when interacting with people who take up these far initial approach distances towards it, as it may be an indication that they are either nervous, or even potentially hostile!

3.5.1 Methodology Review

In all three studies, the floor was marked with tape and metric scale marks in order to aid the distance measurements and this may have influenced the distance results obtained. It is desirable therefore to develop HR distance measuring methods that do not involve floor markings. The PeopleBot™ robots used in these HRI trials have sonar range measuring devices fitted as standard, and laser range measuring system available as an optional fitting. Potentially, these systems can measure distance with a high degree of accuracy. It is desirable to use these systems to measure HR distance in future HRI trials for two reasons. First to eliminate the possible influence of floor markings on HRI trial participants (cf. Koay et al. (2006a) and Walters et al. (2007)). Secondly to investigate, calibrate and establish the baselines and characteristics of human proximity measuring using the robot's own "on-board" sensor systems, in preparation for the future when robot systems will have to interpret and initiate appropriate proxemic social actions autonomously.

The participants in the third PRVE trial were mostly familiar with other robots, and most had very good knowledge of the technology and limitations of current robots. Therefore it could be argued that their reactions would not be representative of the population as a whole. However, the portion of results from this approach trial that could be directly compared with the results from the CADE study, which used robot naive participants, were very similar (cf. Walters et al. (2005a)). This is an indication that when interacting for the first time with a new robot, even technology experienced users may react in a broadly similar way to naive users for their initial perceptions of the robot. It would be desirable for further experiments to compare the time taken by naive and experienced users to form and refine their initial perceptions of any particular robot. It should also be borne in mind that the first real users of domestic and companion robots will probably be those who are most enthusiastic about robots. Experienced users may well be the norm for domestic robotics applications, rather than the exception, especially in the near future.

The informal nature of the PRVE demonstration HRI trial event (where also food and beverages were provided) and the presence of the viewing audience may also have affected the results. The previous trial had provided each participant approximately with 5 to 10 minutes exposure to the robot, but due to the reception nature of the trial event, they may well have spent more time observing others taking part in one or both of the HRI trials. However, this opportunity was also available to all participants who took part in the human to robot approach distance experiment, so any effects due to this were broadly counterbalanced across the two groups. Sabanovic et al. (2006) have argued that it is essential that HRI study methods must be developed for normal situations and environments which cannot be replicated under controlled lab conditions. The results from this trial supports the idea that valid results can be obtained from studies that are carried out in a (relatively uncontrolled) normal human environment. It is essential that HRI trial methods are developed further to enable HRI studies that can take place in normal human oriented environments.

The results gained from these three exploratory studies using PeopleBots™ cannot be generalized to any other type of robot or to any other context or scenario. The PeopleBots™ are mechanoid in appearance so these findings could only possibly be extrapolated to include similar other mechanoid robots. Further trials should also investigate the effects of robot appearance and robot behaviours on HR approach distances.

3.6 Human-Robot Social Space Studies Summary

Substantial individual differences have been found in how people behaved towards the PeopleBot™ robot for the three HRI exploratory proxemic experiments presented here. However, most of the human participants participating in the studies seemed to be receptive to treating the robot in a social way by respecting the robot's interpersonal space after only a short period. Systematic differences for the PRVE trial participants' initial encounters with robots with different voices were observed with respect to the robot's interpersonal social spaces. It is proposed that the greater initial comfortable approach distances to the robot were due to perceived inconsistencies between the robots overall appearance and voice style. This is possible evidence of people modifying aspects of their proxemic behaviour in response to their perception of the robot's non-verbal behaviour. There was a small but significant proportion of both children and adults participants in all the three studies documented here who leave an untypically large initial distance between themselves and the robot, indicating they are uncomfortable in the presence of the PeopleBot™ robot.

3.6.1 Responsibility for Work Performed

The three HR proxemic experimental findings which I have presented for this section were performed as part of three larger separate sets of HRI user trials. I worked together with my colleagues, Kheng lee Koay, Christina Kaouri and Sarah Woods to devise, set-up and run all the HRI experiments for all three sets of HRI user trials which also included a number of other experiments not relevant to this thesis, and which are presented in Walters et al. (2005), Walters et al. (2005b), Walters et al. (2005c), Koay et al. (2005), Koay et al. (2006), Woods et al. (2005),Woods et al. (2005a), Woods et al. (2007), Dautenhahn et al. (2005), te Boekhorst et al. (2006)).

Although all the team members contributed to devising, setting up and running the three experiments and findings presented here relating to HR proximity, this aspect of the trial series was my main interest with regard to this thesis, and I personally motivated, supervised or carried out the development process for the particular experiments presented here. I performed all the statistical and other analyses on the HR proxemic data collected from the three trials documented here, and I am responsible for all the findings, discussions and conclusions presented in this chapter. Many of the original outcomes and findings from the IPE and CADE experiments relevant to this thesis have been published in conference papers (cf. Walters et al. (2005a)) and in a journal article (cf. Walters et al. (2006)). The findings from the PRVE study have been submitted for publication (cf. Walters et al. (2008)).

Chapter 4: Experimental Methodology and Systems Development

This Chapter presents relevant selected findings and outcomes from two sets of HRI trials carried out at the University of Hertfordshire in 2005. The main objectives of these HRI trials relevant to this study were to further develop the experimental HRI methodology and systems, as well as performing more exploratory HRI investigations. The two HRI trials presented here primarily investigated peoples preferences and ratings of robot behaviours in contexts of fetching and carrying objects to and from human participants in a domestic 'living room' scenario. I had proposed a novel Video-based HRI (VHRI) trial methodology, which involved showing HRI scenarios recorded on video to groups of people, and the major focus of my work during this period was in proving and developing the systems, methods, technology and techniques for the methodology. I was also involved in other associated developments of HRI trial methods and systems including improvements in data collection during the HRI trials, particularly to reduce the reliance on human post-trial observations, coding and annotation of the video record. The overall research question addressed in this part of the study relevant to this thesis was:

> *How can video-based experimental methods and data collection technology be developed and applied to HRI experiments ?*

The two sets of HRI trials presented here ostensibly addressed fundamental issues of domestic and companion robot behaviour. Fetching and carrying objects is an important component for a wide range of useful tasks for a robot companion in the home. The eventual aim of these studies was to provide a set of rules and parameters that can provide guidance to the designers and builders of domestic (servant) robots in the future.

First, a pilot series of HRI trials were carried out with one of the main objectives of addressing the above question in addition to a first feasibility test of the proposed VHRI methodology (cf. Woods et al. (2006), Dautenhahn et al. (2006), Koay et al. (2005); Walters et al. (2005a); Walters et al. (2006)).

In light of encouraging results from the Pilot Study, larger scale Main Study VHRI trials were then instigated which investigated further aspects of how robots should approach and serve human participants in a socially acceptable way. This was also used to validate and refine the VHRI methodology over a wider range of contexts and situations. This trial was also used to test other development in data collection hardware and methods (cf. Woods et al. (2006a), Koay et al. (2006), Koay et al. (2006a), Walters et al. (2007), Koay et al. (2007) and Koay et al. (2007a). The two sets of HRI trials and findings are briefly described here:

4.1 Pilot Study Video-based HRI (VHRI) Trials.

To overcome some of the drawbacks of live HRI trials, I proposed to investigate the feasibility of running HRI trials using video footage rather than a full live interaction. Although this Video-Based HRI (VHRI) trial methodology would certainly be inferior to a Live HRI (LHRI) trial session, it was hoped that it would yield valuable results towards the development of live trials. Kidd (2000) found no significant differences between participants' ratings of personality traits for 'present' and 'remote' (through video) cases of an interaction with a robot head. Shinozawa et al. (2005) reported that comparing a robot's recommendation behaviour with an on-screen agent's, for human decision making, depended on the interaction environment and that geometrical consistency between the interaction environment, and robots and on-screen agents was important. Paiva et al. (2004) reported that even synthetic (cartoon-like) characters in virtual environments, displayed on 2D computer displays, were readily empathized with by children as they enacted various scenarios. Though these findings are not directly applicable to the medium of real video recordings, it showed that that even a simple screen based representation of an interaction (between computer agents in this case) can provoke a reaction by observers which is comparable to a real life situation or scenario. This provided some supporting evidence that believable relationships can be created through the medium of video.

It was therefore thought possible that using videos of actual robots, which are more realistic than virtual or synthetic characters, could result in HRI trials that are even closer to resembling real live interactions. VHRI trials have the potential advantages to:

1. Reach larger numbers of participants as they are quicker to administer and by exposing groups of participants to the HRI scenario simultaneously.

2. Easily incorporate participants' ideas and views into later video trials simply by recording extra or replacement scenes into the video based scenarios.

3. To prototype proposed live trial scenarios to avoid wasted effort and test initial assumptions.

4. Allow greater control for standardised methodologies (i.e. exactly the same robot behaviours, exact trial instructions).

As this was an unexplored area of with regard to HRI trials and investigations, it was first necessary to explore and verify that VHRI trials were able to provide comparable results to LHRI trials, and also under what circumstances. A Pilot Study (PS) to compare the results from both LHRI and VHRI trials was developed to begin exploring the following main research question:

> *Would VHRI trial scenarios provide results that are comparable to results obtained from LHRI trials?*

Investigations into this main research question also should also address the related issues of under what circumstances would VHRI trials provide comparable results to LHRI trials, and what would be the likely limitations of VHRI trials in gaining valid human responses to HRI scenarios.

4.1.1 Pilot Study VHRI Experimental Method and Procedure

The Pilot Study scenario and experiment procedure was based on a previous HRI experiment which had been carried out for a Demonstration HRI Trial event which was part of an evenings entertainment at the AISB Symposium at UH in 2005. This was the other demonstration HRI trial, which ran alongside the PRVE trial and which was referred to in Chapter 3. This HRI previous HRI trial had involved the PeopleBot™ robot approaching seated participants from different directions in order investigate preferences for robot movements when handing over objects in a fetch and carry scenario. The detailed findings from this demonstration HRI trial can be found in Woods et al. (2006). In order to obtain comparable data, clarify some of the results obtained from this previous HRI trial and for the purposes of the Pilot Study VHRI comparison, it was necessary to perform the same HRI trial procedure under tightly controlled experimental conditions. Otherwise, the HRI trial experimental set-up and method were the same for both the demonstration and pilot study trials. The Pilot Study VHRI experiment trials were carried out in a converted conference room. The chosen scenario, as with the previous demonstration HRI trial, involved a robot using different approach directions to bring a seated participant an object. The aims of the trial were to find out about participant preferences for the robot approach directions.

The room was partitioned into two areas; a video trial area and a live trial area. There was a gap in the partition, so that it was possible to move between the two areas (see Figure 26) but not possible for participants to see the other area while carrying out the respective video or live trials. The live trial area resembled a simulated living room with a chair and two tables. The participant was seated in the chair throughout the live trial which was positioned halfway along the rear wall (point (9), Figure 26). To the left front and right front of the chair, two tables were arranged (with room for the robot to pass by) in front of the chair. One of the tables had a television placed upon it; the other had a radio and CD player. The robot was driven to the appropriate start position by an operator seated at a table in the far corner of the room. participants were told that the robot would be controlled by the operator while it was driven to the three start positions, but would be approaching them autonomously to bring them the TV remote control. This was reinforced as the operator made notes and did not press any of the robot control keys (on the robot control laptop) while it approached the participant.

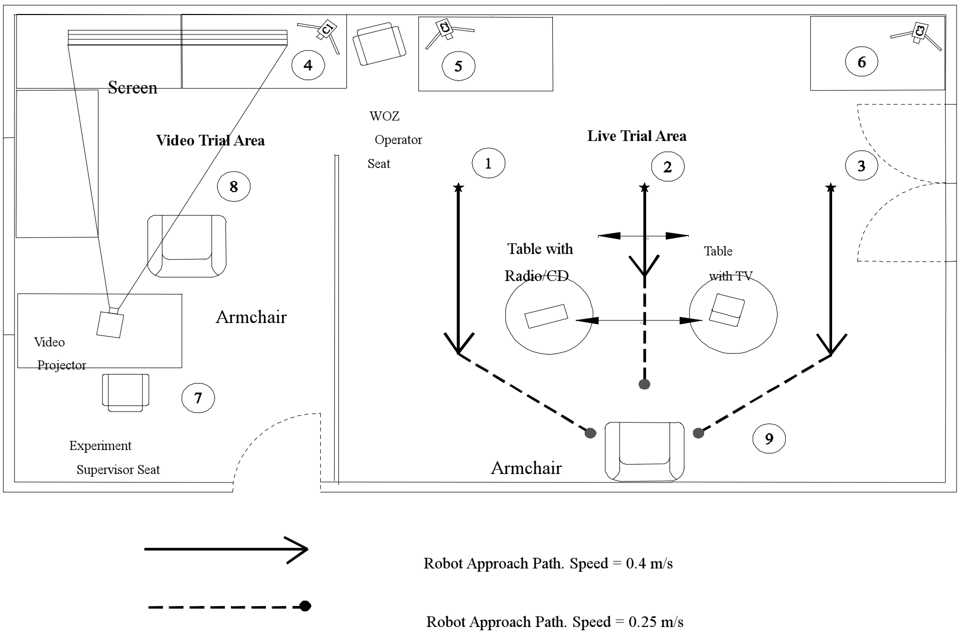


Figure 26: Diagram of video and live trial experimental areas

The video trial area contained a video projection screen and projector for playing the VHRI trial scenarios. The videos were all recorded in the live trial area, with an actor playing the part of the participant. The actor was male, and the narration voice which introduced and set the scene for the HRI trial scenario was also male. The videos were recorded using a mixture of first and third person points of view. The third person views showed the overall positions and actions of both robot and (actor) participant. Then by switching to a first person view (from the perspective of the participant sitting in the chair as the robot approached) a viewer saw the robot approaching in a way that was as realistic as possible and could gain some spatial perspective (see Figure 27 for example screen shots).

An identical scenario was used for both the video and live HRI trials and took place in a (simulated) living room (Figures 26 and 27). It was introduced either by the experiment supervisor for the live trial, or by the narrator for the video based trial. The context was that the participant had arrived home from work and rested in an armchair (point (9), Figure 26). The participant then asked the robot to fetch the remote control. It was explained to the participant that the robot was new to the household and it was necessary to find out which approach direction the participant preferred; either from the front (2), the left (1) or the right (3) (see Figures 26 and 27). In order to justify the robot fetching the remote control, one of the tables had a (switched off) TV set upon it. The other table had a CD-Radio unit. The expectations prior to the trials were that participants would prefer the approach from the front, since the robot was then fully visible at all times.

Figure 27: Examples of first and third person views in the HRI videos.

We were aware from a similar previous live demonstration HRI trial that the TV was a natural focus of participants' attention and could have influenced the choice of preferred robot approach direction. Therefore, half the trials (for both live and video versions) were carried out with the TV on the left hand table, and the other half with the TV on the right hand table.

Each participant experienced the robot approaching from three directions, front, left and right, in a counterbalanced order sequence covering all six possible permutations of the three robot approach directions. This was used for both VHRI and live HRI trials. As a consistency check, the three robot approach directions were also repeated (in a different order) for each trial. In order to counterbalance for effects due to the order in which participants experienced the video and live trials, half the participants were exposed to the live trial first, then vice versa for the other half of the trials.

Fifteen participants (9 (60%) males; 6 (40%) females) individually participated in the study. The mean age of the sample was 33 years (range 21-56 yrs). Only one participant was left handed. Four participants were secretarial staff from the University of Hertfordshire, 5 participants were MSc students studying 'Artificial Intelligence', and the remaining 6 were research staff in the Computer Science Department at the University.

A short introductory questionnaire was used to gain the necessary demographic and personal details from the participants. At the end of each video or live HRI trial a short questionnaire was used to assess the participants' views on approach direction, approach speed, stopping distances, comfort levels and practicality for the different approach directions. After both video and live trials had been completed, participants participated in a semi-structured interview with a psychologist. The interview was carefully designed so that no leading questions were asked. The interviewer was able to follow up answers to gain a deeper insight when necessary. The main purpose of the structured interview was to assess the participants' views on the trial procedures and methodology, establish any weaknesses and find out how the trial could be improved from the participants' point of view. The participants' reactions to both live and video based HRI trials were recorded on video tape.

4.1.2 Findings

The relevant findings from this study are outlined here. A more complete coverage can be found in Woods et al. (2006) and Walters et al. (2007a). Most participants disliked a frontal approach when seated. Most participants preferred to be approached from either the left or right side, with a small overall preference for a right approach by the robot. However, this is not a strong preference and it may be disregarded if it is more physically convenient to approach from a left front direction. There was a good overall agreement between the video and live HRI trial results:

1. The level of agreement between participant responses for the preferred robot approach direction was relatively high (60%) between the live and video trials. Discrepancies were mainly due to the fact that participants did not have strong preferences for either the left or right robot approach direction and sometimes changed these preferences between the video and live trials.

2. Very high levels of correspondence (85%) were found for participants least preferring the front robot approach direction in both the live and video trials.

3. Moderate to high levels (60-80%) of agreement were found for perceptions of the robot's stopping distance from the participant, for each approach direction in the live and video trials.

4. High agreement (87%) was found for participant ratings of the robot's speed between the live and video trials.

5. No significant differences were revealed between participant ratings of how practical and comfortable the different robot approach directions were for both the live and video trials.

6. Participant ratings for the realism of the video trials in comparison to the live trials were moderately high, although 93% stated that they preferred interacting in the live trials.

These results supported findings from an informal earlier study (the other demonstration HRI trial run at the same event as the RVAE Study, cf. Chapter 3.4) and also provided support for using video based HRI trial methods. It was thought that participants might find it difficult to perceive the robot approach distances, and approach speed through the video medium, but this seems to not be the case. There were non-significant differences between findings for participant ratings of the robot approach direction and comfort levels between the live and video trials. This indicated that participants were able to report reliably on their experience of how comfortable they would feel with different robot approach directions through video footage.

Most participants preferred the live robot-interaction trials. This was not surprising as live trials seem more interactive, likely to be more fun, and more engaging compared to watching the interactions involving a stranger on a screen. The embodiment experience of being part of a live-set up is also likely to be much more beneficial for assisting in the perception of speed, distances and different robot movements compared to video footage. However, most also reported that the video robot trial experience was representative of same scenario from the live trials. Participants' overall ratings of the 'realism' of the approach direction robot trials was moderately high and most of the improvements that participants cited were related to the environmental set-up, and context, rather than characteristics of the robot. The participants' also made suggestions that reinforced the notion that our future robot trials should take place in a more naturalistic 'messy' living room set up, which is more representative of a realistic home environment.

4.2 Main Study VHRI Trials

The specific aspect that the Pilot Study VHRI trials considered was how a robot should approach a seated human. Therefore, the relevant aims of these trials were:

To confirm and consolidate the results previously obtained from the pilot studies.

To extend the range of human-robot interaction situations and scenarios from those studied previously.

To verify previous pilot trial results that suggested that VHRI trials obtained results which were comparable to those obtained from live HRI trials based on the same HRI scenario.

A recommendation from the experiences of running the previous three HRI trials, (cf. Chapter 3), and the pilot trial (cf. the previous section) included one that future HRI experiments should be carried out in more 'natural' human settings. It was therefore seen as a desirable development to use experimental domestic settings that were as naturalistic as possible. In order to provide a more ecologically valid experimental environment, an apartment near to the University was rented, referred to here as the "Robot House", and the main living room was furnished and used as the venue for this next set of HRI trials. Feedback from the participants indicated that they thought the Robot House was not like a laboratory, they felt less as if they were being tested and the perception of the experimental area was more 'neutral' than a laboratory. In total, four different scenarios were studied in these trials where a robot approached the participant who was located in the living room of the robot house:

1. *Seated on a chair in the middle of an open space.*

2. *Standing in the middle of an open space.*

3. *Seated at a table in the middle of an open space.*

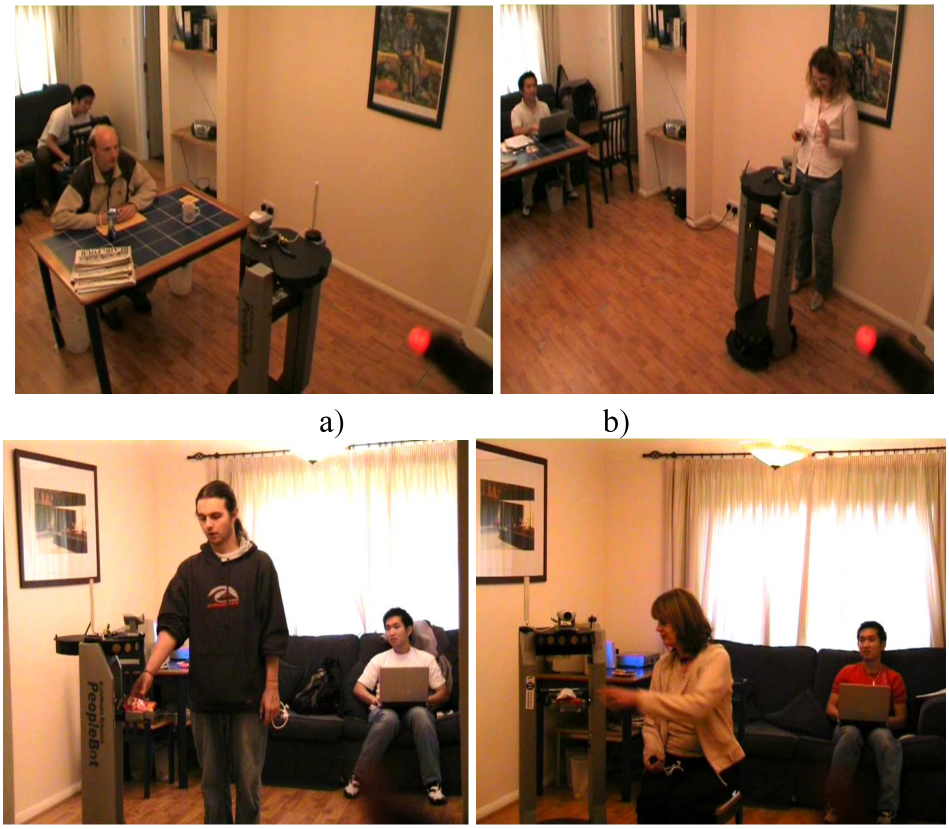
4. *Standing with their back against a wall.*

These particular interactions were chosen as they were typical approach situations which would typically be encountered in a wide range of fetching and carrying tasks that a domestic robot might be expected to carry out. It is hoped that once the appropriate approach behavior expected of robots is known, these actions could then be used as 'primitive' robot action components which could be sequenced appropriately into more complex task scenarios involving a robot approaching a human. These Main Study VHRI trials were performed in the living room of the Robot House. There were a total of 42 participants, who each experienced two of the scenarios from the four described above.

4.2.1 Main Study VHRI Experimental Method and Procedure

The studies used a commercially available PeopleBot™ with standard equipment fitted, including a pan and tilt camera unit and a standard short reach lifting gripper which was adapted to form a simple tray in order to fetch and carry objects as required. During the trials, most of the furniture was arranged at one end of the room, to provide a large clear space for carrying out the HRI trials. A chair and/or table were moved to the central position as required for the trial scenarios where the participant was to be seated in the middle of the room or at the table. First, a short introduction video was shown to the participant, followed by consent forms and introductory questionnaires before the robot to human approach trials began. A main aim of this study was to extend the range of scenarios tested. The main part of these HRI trials relevant to this study was to verify the findings from the pilot trials with regard to the use of the VHRI trial methodology. This involved participants undergoing alternating live HRI trial and VHRI trial runs. The order of the HRI and VHRI scenarios was changed for each participant, and the first trial was alternated between VHRI and HRI trial.

The VHRI trial videos were shot in The robot house with an actor playing the part of the participant. I developed a set of guidelines, based on the experience gained from running the previous VHRI trials, for producing the VHRI videos which specified the mix of first and third person views to be shown and the forms of editing and effects allowed in an HRI trial videos. The guidelines provide a standard formula for VHRI videos to follow: An initial wide angle view of the HRI area is always shown to establish the initial spatial relationship of robot and actor(s) and provide an overview of the scenario and the HRI. Then a series of first and third person views which show the action primarily from the users point of view. There should be no first person views from the robot's point of view, and action should preferably be shown happening in "real time" with no quick cut edited sequences to artificially enhance the interest of the video. Where a cut away is made to signify a passing of time a fade out - in transition should be employed. A subtitle to explain what was happening during the period cut by the fade transition is acceptable.



a) b) c) d)

Figure 28: Views from the Robot Approach Direction Trials. a) Seated at table, b) Standing against wall, c) Standing in middle of room, d) Seated without table.

Two video cameras recorded each participant as they experienced the live HRI trials; one fixed overhead wide angle camera with an overview of most of the experimental area, and a tripod mounted video camera which recorded a closer view of the participant. A single camera recorded the participants reactions as they underwent the VHRI trial. Hűttenrauch et al. (2006) had used a method of overlaying photographs of their HRI trial with a semi-transparent metric grid to facilitate analysis. Inspired by this method, I had the idea to lay out the floor area with adhesive tape in a 0.5m grid pattern and take calibration pictures from the exact viewpoint of the fixed overhead video camera when the trials were complete. I then overlaid this photograph transparently onto the video recordings from the overhead camera in a separate post processing operation using video editing software (see Figure 28). The process is demonstrated in Walters et al. (2007b) where video clips from more recent follow up trials were presented.

During the trials, participants were asked to use a small wireless signalling device whenever they felt uncomfortable with the proximity of robot. I developed the device from a prototype Comfort Level Device (CLD) which I had made for a previous HRI trial (cf. Koay et al. (2005)).

Figure 29: The Comfort Level Device

This new version consisted of a small key-fob sized transmitter with a single button which was easily pressed by the trial participant (Figure 29). When the signal was received by a receiver, I added a small LED light to the receiver which was illuminated whenever the CLD device button was pressed. I had the idea to mount the receiver LEDs to the fixed video camera, so that the light flashes were recorded onto the corner of the video recordings of the trials (Figure 28). In this way, the video recording was automatically annotated with the participants' discomfort signals.

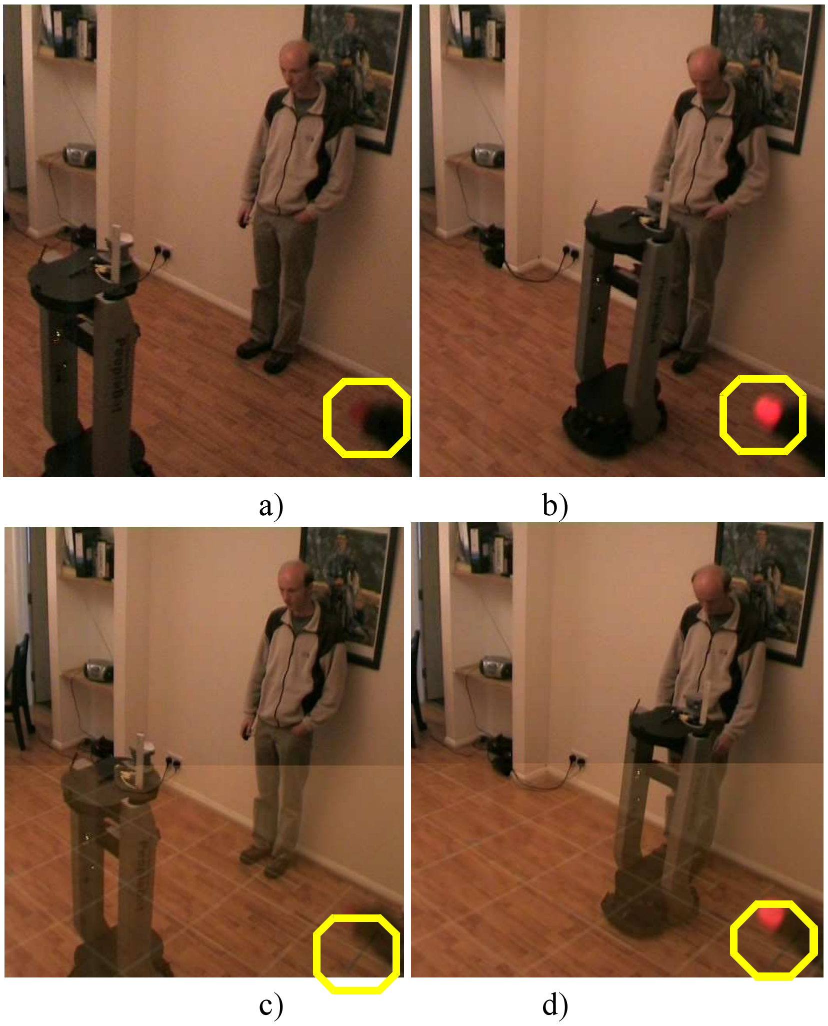


Figure 30: Clips from the HRI trial videos illustrating the use of the CLD (red light-circled) in b) and d). The video is then overlaid with a 0.5m grid in c) and d).

The distance between the robot and human participants was able to be estimated (to the nearest 0.25m increment on the overlaid grid 0.5m grid) each time the CLD signal was perceived on the post processed video recording. It was intended that these comfortable robot approach distance measurements would be an important part of the key trial data to be considered in this study.

After each HRI approach trial a questionnaire was administered to gain the participants' categorical (5-point Likert scale) ratings of preferences regarding: the most preferred and least preferred approach directions, and the approach directions judged as most and least efficient.

A summary of the main results are provided here. For full details of the statistical analysis of the questionnaire data, and the video based HRI methodology verification results, see Woods et al. (2006) and Walters et al. (2007a).

4.3 Main Study VHRI Findings.

4.3.1 Summary of Questionnaire Results.

The statistical analysis of the questionnaire data included a non-parametric Friedman analysis of variance by mean ranks to determine whether there were significant differences between participant comfort rating preferences for the different approach directions. The Friedman test was also used to analyse participants' ratings of the robot's task efficiency. A full statistical analysis of these results were also used to verify and support new the HRI video based methodology described previously. Paired t-tests for matched samples were carried out to determine whether there were any significant differences between the subjects approach direction preferences for both live and video based HRIs. A more complete coverage can be found in Woods et al. (2006a).

Seated at Table Condition - Participants rated the front left and front right approaches as the most comfortable and found the rear approaches the least comfortable. Participants had no preference for the level of task efficiency and the approach direction used by the robot.

Standing Against a Wall Condition - Participants rated the front direct approach as less comfortable compared to the front left and front right approaches. No significant differences were found between participant robot task efficiency ratings for the robot approach directions.

Seated in Middle of Room Condition - Participants rated the front left and front right approach directions as more comfortable than the rear approaches and the frontal direct approach. Participants did not display overall preferences for a more or less efficient robot approach direction.

Standing in Middle of a Room Condition - Participants clearly felt the least comfortable with the rear central approach direction and were the most comfortable with the front left and front right approaches. The rear central approach was rated by participants as being the least efficient, and the frontal approach. front right, and front left approaches were rated as the most efficient.

Video Based HRI Trial Findings - Consistent findings were revealed comparing live versus video scenario conditions, based on results from our study investigating people's preferences for different robot approach directions in different scenarios and scenarios. The one exception was for robot task efficiency for the 'seated at the table' scenario, where subjects expressed an approach direction preference for task efficiency for the video condition, but not for the live condition. Overall, the front left and right approaches were rated by subjects as the most comfortable for all the different scenario scenarios. The rear approaches and front direct approaches were rated as being the least comfortable across different scenario scenarios.

4.3.2 CLD Distance Measurements

The results from the CLD comfortable robot approach distance measurements were obtained and are given in Table 7. The distances were measured from the closest part of the robot base to the human participant to the closest part of the participants' feet. The mean and Standard Deviation (SD) values for the rear central approach direction are not very informative (as N=2, df = 1), so are not shown in the included diagram. The mean distance values for the front left approach direction are also unreliable due to the small size of the samples. Unfortunately, the number of samples was much smaller than expected and there were not enough valid results to perform a full range of statistical tests taking into account the four approach situation conditions. As can be seen in the Table in Figure 7, most participants only used the CLD for one or two approaches at best and instead of a possible maximum of 285 distance measures, only 42 measurements in total were obtained.

Table 7: Distances Obtained from the CLD for the HRI Trial Conditions

	Robot Distance (m) when CLD was Operated					
Approach Direction	N	Mean	Mode Freq.	Minimum	Maximum	Std.Dev.
Front	13	0.44	6	0.25	0.75	0.18
Front Right	18	0.46	8	0.00	1.00	0.29
Front Left	7	0.54	Multiple	0.25	1.25	0.39
Rear Right	6	0.50	7	0.25	0.75	0.22
Rear Central	2	0.63	None	0.50	0.75	0.18
Rear Left	7	0.68	4	0.25	0.75	0.19

	Robot Distance (m) When CLD Operated									
Approach Conds.	Front	(N)	Fr. Right	(N)	Fr. Left	(N)	R. Right	(N)	R. Left	(N)
Seated Middle	0.38	4	0.43	10	0.75	1	0.63	2	0.75	3
Standing Wall		0	0.44	4	0.25	3				
Seated Table	0.58	3	0.75	1	0.75	1	0.44	4	0.63	4
Standing Middle	0.42	6	0.50	3	0.75	2		0		0
All Groups	0.44	13	0.46	18	0.54	7	0.50	6	0.68	7

Although a thorough statistical analysis was impossible, some tentative observations can be made. In particular, the CLD measured frontal robot approach distances tended to be closer when the participants were standing or sitting in open space. Also the CLD measured approach distances tended to be closer for the front right approach directions. The indicated approach distances for rear left and rear right may indicate that some participants allowed the robot to approach slightly closer from the rear left direction, as opposed to the rear right direction when seated or standing. However, it must be stressed that most participants did not use the CLD more than once or twice only, and these results must be treated with caution. However, the feasibility of gaining HR proximity data direct from the robot range sensors was demonstrated.

4.4 Discussion of Findings from VHRI Approach Trials

Based on the responses from questionnaires (cf. Woods et al. (2006a), and Woods et al. (2006)) from both the pilot study and the confirmatory study into robot to human approaches, overall the front left and front right approaches were rated by participants as the most comfortable for all the different scenario scenarios. The rear approaches and front direct approaches were generally rated as being the least comfortable across different scenarios. However, participants standing in the middle of the room actually preferred the direct frontal approach for task efficiency reasons, in contrast to the seated conditions. Seated participants were shorter than the robot, and a few stated that they found a direct approach by the robot slightly intimidating. In the scenario where the participants were standing they would normally have been taller than the robot and this might provide the reason for them not finding the robot so intimidating in this condition.

Only 15 participants participated in the pilot study, many with a robotics or computer science related background and this may have biased the results. However, such participants are most likely to be future customers of a robot assistant in the home (cf. Chapter 3) and in the previous investigations into HR proxemics (cf. Chapter 3, & Walters et al. (2008)) which included HRI experiments with both experienced and naive participants, similar results were found with respect to initial approach distances between both robot experienced and naive groups of participants. The participants in the second study were more balanced in terms of their backgrounds, and the results obtained were broadly comparable to those from the pilot study and the previous informal demonstration HRI trial event (cf. Section 4.1), indicating that the (technical) background of participants did not affect these results in a systematic way.

The current findings offer scope for future work into the feasibility of using video based HRI trials to aid the design and implementation of live interaction studies. Surprisingly, the results obtained from both sets of live and video based HRI trials were comparable for issues of robot speed, space and distance. Both first person and third person views were used for the video trials and it is likely that this enabled participants to get a realistic perspective of space and distance for the robot. However, it may well be the case that results obtained by video based trial methods would be more suitable for exploring participant responses to robot gestures, robot appearance, and robot dialogue. It could also be that the more contingent the interactions between a robot and a participant in a trial, the less suitable video based HRI trials will be. The timing and synchronization of movements play an important part in regulating and sustaining meaningful human-human interactions. Developmental psychologists (e.g. Murray & Trevarthen (1985)) have shown that while babies happily interact with their mothers via live video, they get highly distressed when watching pre-recorded or replayed videos of their mothers (as it lacks the contingency between mother's and baby's behaviour). However, for the particular research questions that have been considered in the present studies, in the context of robot motion planning and approach directions, the contingency of robot and human movements plays a less crucial role and thus have lent themselves to investigations by video based HRI trials. The quality of the robot trials could also be enhanced if professional camera techniques are adopted and guidelines developed to create video material for HRI video trials.

Unfortunately, most participants did not use the CLD device regularly and thus severely restricted the data sample size with regard to RH approach distances for the Main Study VHRI experiment presented here. The sample size was too small to provide a good basis for proper statistical analysis, though there are some tentative indications that are supportive of some of the findings obtained from the questionnaire data (cf. Woods et al. (2006a)) and are consistent with findings from the previous HR proxemics findings (cf. Chapter 3, Walters et al. (2005a), Walters et al. (2006) & Walters et al. (2008)). This was an important provisional finding and if confirmed it would allow aspects of human users' preferences to be inferred from the simple CLD signalling device. The CLD could perhaps actually be used while HRI trials are in progress and thus avoid or reduce the need for time consuming post trial questionnaires. There are also other advantages with regard to immediacy and not having to rely on participants' memories for their reactions to more complicated HRI scenarios. In the future during a 'training' phase perhaps, the robot could also adapt or refine its spatial (or other) behaviors based on the CLD data received. To avoid the situation where many, or even most, participants fail to use the CLD, in future HRI trials a strategy of reminding participants to use the CLD for every trial run should be implemented.

Overall, encouraging results were obtained comparing the agreement between participant responses towards robot approach directions for live HRI and VHRI trials. This has positive implications for us and other researchers designing future HRI trials. VHRI trials could be used as a complementary research tool to yield valuable results regarding peoples' opinions towards various aspects of a robot's behaviour and/or physical capabilities. VHRI trials are more economical compared to live interactions and allow the designers and researchers greater levels of control and standardisation over the set-up and procedure of the trials, which is sometimes difficult when conducting live HRI trials.

4.5 Summary

These further HRI trial findings have provided further evidence verifying and extending the applicability of results from previous studies. They have also verified and tested the video based HRI trial methodology for four fundamental HRI situation and contexts which may occur in a range of typical robot 'serving' or 'object fetching' task scenarios with standing and seated humans (Woods et al. (2006), Woods et al. (2006a) and Walters et al. (2006)).

Other outcomes from the work presented here are: a) further development of the CLD methodology and systems, b) the demonstrated feasibility of the associated technique of automatically annotating HRI trial videos with CLD data in order to gain distance measurements, c) upgrading of the robot systems and appearance to include more human-like features ready for use in the next series of HRI trials. While the use of CLD annotated video data has been shown previously (Koay et al. (2006), Koay et al. (2006a)), this technique has been extended by using the video grid overlay to obtain both concurrent position and distance information of both robot and human directly from the video record (Walters et al. (2007)). Future work will have to expand on these lessons and further develop methodologies to investigate human approach preferences and distances in naturalistic HRI scenarios.

4.5.1 Responsibility for Work Presented here

As the originator of the idea of using a VHRI methodology, the main scientific research focus of my work during this period was on the development of the VHRI research method and systems. I produced and edited the videos used for both the HRI trials documented here and developed much of the associated VHRI trial systems, methodology and procedure. I designed and constructed the first and second versions of the CLD hardware (cf. Appendix IV) and devised the technique of overlaying a grid onto the CLD annotated video recordings (cf. Walters et al. (2007b)) in order to facilitate the continuous recording of position and orientation for robot and humans in the experimental area. I performed the grid overlay processing and observation of the Main Study VHRI trial videos of the live versions in order to obtain the CLD signals which were used to measured robot to human approach distances, and I performed the (limited) statistical analysis of this data Walters et al. (2007).

The first Pilot Study VHRI trial documented here was set up and run mainly by me and my colleague Sarah Woods. She and I, along with another colleague, Kheng Lee Koay set up and ran the second Main Study HRI Trial presented in this chapter. Sarah was mainly in charge of devising questionnaires and the statistical analyses of the questionnaire responses for both of these studies (cf. Woods et al. (2006) & Woods et al. (2006a)). Kheng Lee's main focus during this period was on developing the control software for the PeopleBot robots and in further analysis of the results obtained from previous and other HRI trials (cf. Koay et al. (2006) & Koay et al. (2006a)).

Chapter 5: Robot Appearance and Behaviour VHRI Trial

In accordance with the recommendations of Chapter 3, an exploratory investigation of human perceptions of consistency of robot appearance and behaviour was carried out. This pilot Robot Appearance and Behaviour Experiment (RABE) used the novel VHRI trial method presented previously in Chapter 4. Changes were made to the PeopleBot™ robot(s) to provide a range of three different appearances. The rudimentary manipulation capabilities were also enhanced from the basic single Degree of Freedom (DoF) gripper and the simple 1 DoF pointing arm (used in the previous HR Proximity Trials, cf. Chapter 3) by providing a set of more versatile manipulators in the form of humanoid arms. These were more human like in appearance, though still obviously robotic, and capable of some simple gestures. The videos featured the PeopleBots™ with the new hardware additions which provided three different robot appearances. These were labelled Mechanoid, Basic and Humanoid. These robot systems are also used in next series of live HRI Trials which are presented in the following Chapter 6.

5.1 Robot Systems Development for VHRI Trial.

In order to provide the three different robot appearances ranging from mechanoid to humanoid to be used in the VHRI RABE trial videos, I designed and built additional hardware systems for the PeopleBot™ robots. I produced a set of programmable humanoid robot arms which were used for the humanoid robot in the videos, and also for further investigations in HRI trials incorporating robot gestures. I also designed and produced a humanoid robot head which was able to be easily fixed onto the PeopleBot™ robots to provide a more humanoid appearance. Both the humanoid head and arms are shown fitted to a PeopleBot™ robot in Figure 31. Both these robot hardware add-ons were also used to modify the robots' appearances in the further live studies presented in Chapter 6.

In the VHRI RABE trial videos it was proposed to use a range of three robot appearances. Therefore to obtain robot which was approximately intermediate in human-like appearance between the Mechanoid (unadorned PeopleBot™) and Humanoid (with humanoid arms and head attached) a simple cylindrical head was built by my colleague, Kheng Lee Koay and used in conjunction with the simple lifting arm from the IPE HRI trials (cf. Chapter 3).

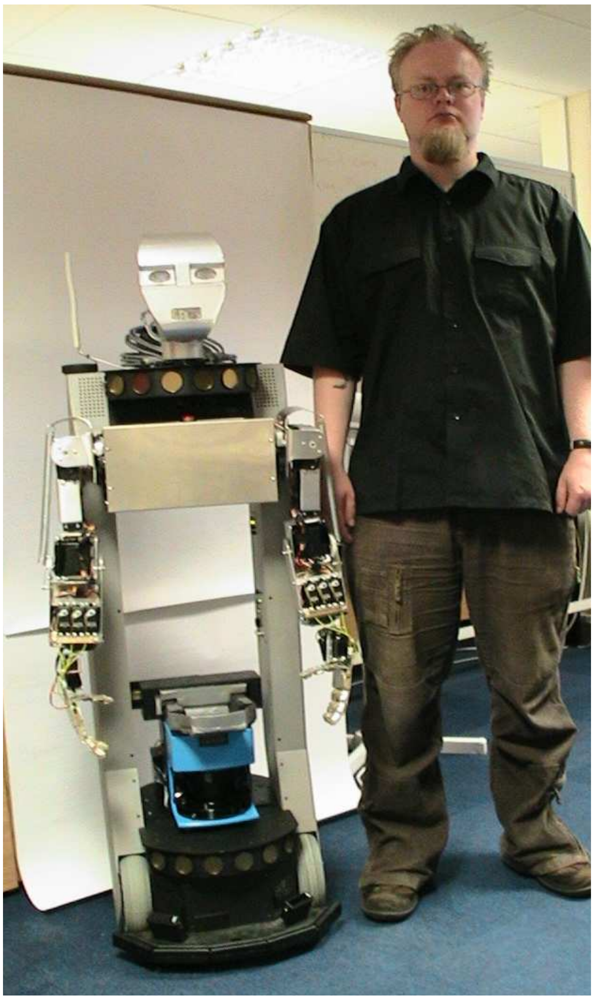


Figure 31: A "Humanoid" appearance PeopleBot™ robot with Humanoid head and arms fitted.

5.1.1 The Humanoid Robot Arms

The Humanoid robot arms were made to be fitted to the PeopleBot™ robots primarily in order to provide a more humanoid appearance. Each arm has 11 Degrees of Freedom, with seven actuated joints for the main arm linkages, including one redundant joint. The hands incorporated another four movements, two DoF for the thumb, 1 DoF for the index finger and

1DoF for the other fingers combined. This combination of finger movements allows the robot to make a range of common pointing and waving hand/arm gestures.

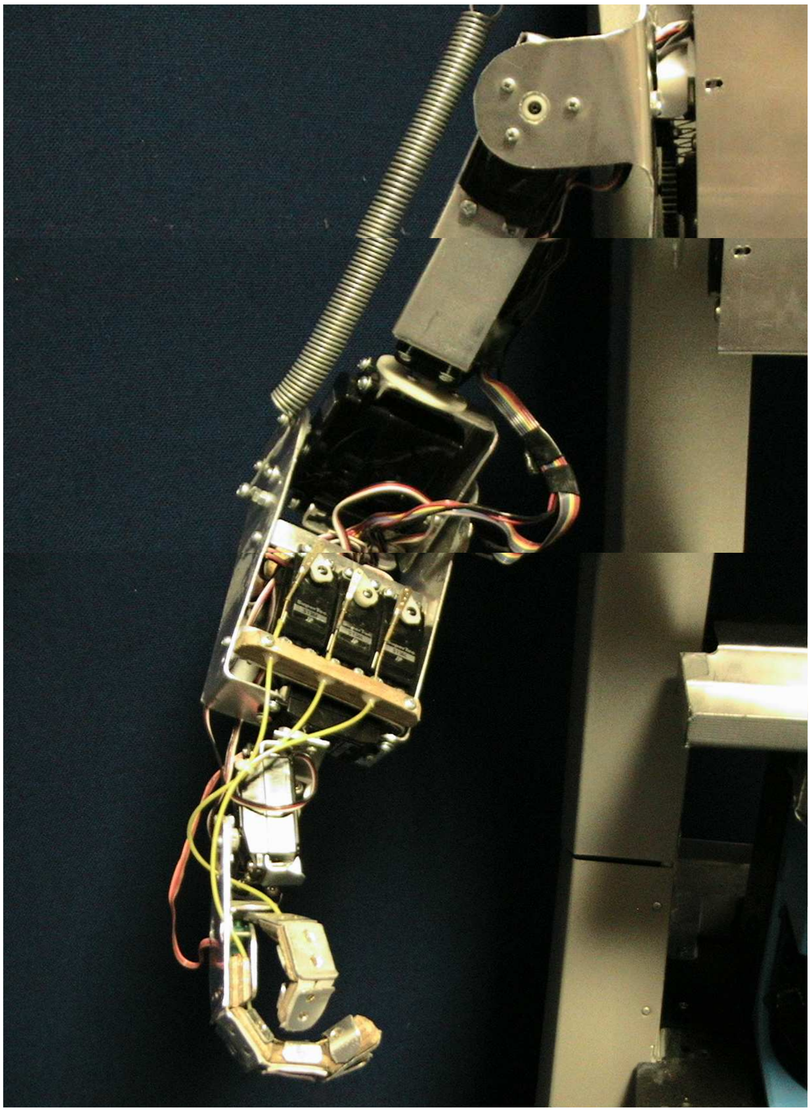


Figure 32: The Humanoid robot arms attached to the PeopleBotTM robot.

The payload capacity of the arms at full reach was approximately 300 grams, as the prime purpose was to allow the robot to make more human-like gestures. The arms utilised standard Radio Control servos as actuators. The main shoulder and elbow joints used very powerful "yacht" type RC servos, while the joints further from the shoulder, used the more lighter standard types. Two arms were mounted on the controller box, which contained two dedicated linked micro controller systems (Figure 33) which were programmed in firmware to provide the low level supervisory arm joint position and control capability (cf. firmware program listing in Appendix I).

The controllers receive high level position and movement instructions from a task level custom or Graphic User Interface (GUI) program (current version now TRAPS V1.5) running on a host computer (Figure 34). This allows both arms to exhibit interpolated coordinated motion, but to be easily controlled together via a high level serial interface. For the RABE VHRI trial video, the robot arm gestures were controlled from a separate laptop, but eventually it is intended to integrate the arms directly into the PeopleBots™ on-board Linux computer.

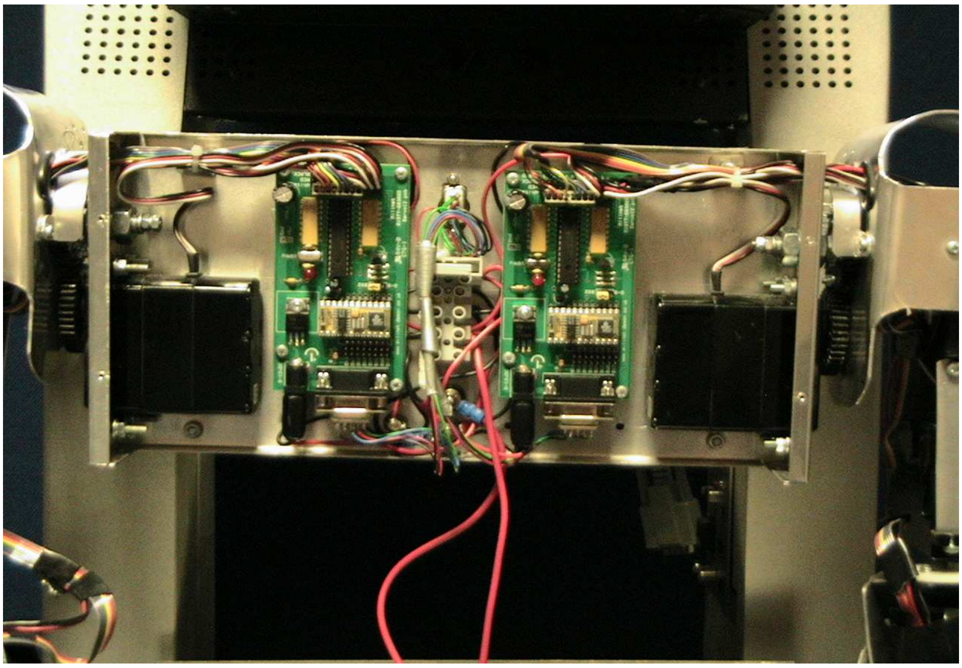


Figure 33: Detail view of the Humanoid arms dual dedicated micro controllers which provide low level coordinated movement control.

Note, both the GUI and Application Developer Interface (ADI) are written in the interpreted programming language Python, and implemented as Python classes which allows any software developed in Python to run equally easily on Windows, Linux or MAC Computer platforms. More hardware details and program listings are provided in Appendix I.

Figure 34: The Humanoid robot arms GUI program, TRAPS V1.5, running on a Windows host computer.

5.1.2 The Humanoid Robot Head

In order produce a more humanoid appearance for the PeopleBot™ robots, it was necessary to produce a humanoid head. The head was designed to have the same proportions as a human head, but to be obviously robotic in appearance with a finish similar to that on the PeopleBot™. The rationale for the head design specification was to produce a head which was perceived by people as obviously robotic, but which had simplified attributes which could be interpreted as simple facial features, including simplified eyes, eyebrows, nose and mouth. The overall look of the head was inspired partly by illustrations from science fiction comics and films, as it thai would hopefully fit with any preconceptions by participants. The robot head used Light Emitting Diodes (LEDs) incorporated into the simplified eyes and mouth features in order to provide a simple method for the robot to produce rudimentary signals.

The humanoid robot head was constructed from three pre shaped cardboard sheets, glued and taped together and sprayed with aluminium paint to provide a suitably solid metallic robotic appearance (Figure 35). The eyes and mouth were fitted with darkened transparent plastic film, behind which were fitted matrices of small LED lights, red for the mouth and blue for the eyes. By switching the LEDs in different patterns, the robot could show various "expressions". For producing the videos used in the VHRI trials presented later in this Chapter, the LED patterns were switched using a system of manual switches. It is however, intended to interface the switch control for the LEDs directly to the PeopleBot™ system, so that in future HRI trials the LED patterns can be controlled directly from the on-board Linux computer. The humanoid head was fixed to the PeopleBot™ by means of a quick release bracket, which bolted onto the top section of the PeopleBot™ structure. For more details of the Humanoid robot head structure and operation, see Appendix II.

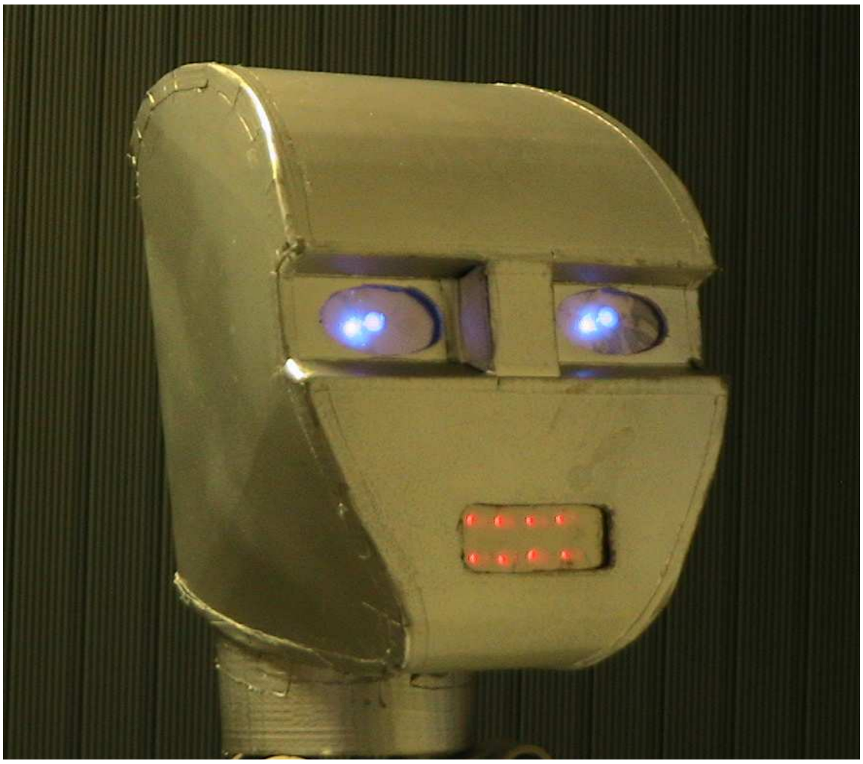


Figure 35: Close up detail view of the Humanoid robot head

5.2 Robot Appearance and Behaviour Experiment (RABE)

It was hypothesized (cf. Chapter 2), that robot appearance as well as robot behaviour were important factors affecting how people form perceptions and relate socially to robots. It was concluded in the literature review in Chapter 2, that people did not want domestic robots to exhibit a realistic human appearance (e.g.. Khan (1998)), but would like the robot to communicate in a more human way. We have also argued that the robot should also exhibit socially acceptable behaviour Dautenhahn et al. (2005). Therefore, this study addressed two main research questions related to these issues:

> *What is the importance of consistency between robot appearance and behaviour for less human-looking robots?*
>
> *Would people prefer a degree of human-like appearance and behaviour attributes in robots that they interact with?*

5.2.1 RABE Method and Procedure

The context chosen for the study and the associated VHRI trials was that of a domestic robot attracting human attention using a combination of visual and audible cues. Previously, we have employed live human-robot experiments in which humans and real robots typically interact in various relatively controlled scenarios (e.g. Walters et al. (2005) and Dautenhahn et al. (2006)). Live HRI trials are generally complicated and expensive to run and usually test a relatively small sample of possible users. The methodology chosen was adopted from the VHRI methodology described in Chapter 4. In these studies, the results obtained from participants who viewed a video recording of another person participating in interactions with a robot, are comparable to those obtained from participants in live interactions. For full details see Woods et al. (2006) and Woods et al. (2006a) where results justify the choice of VHRI trials for this study.

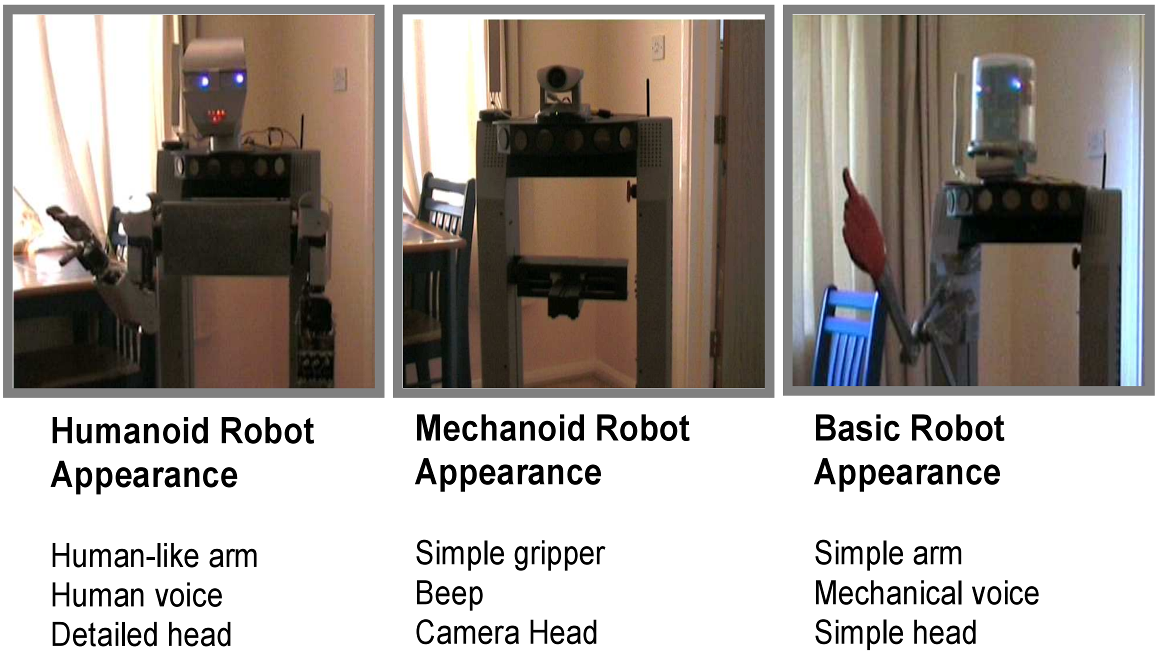


Figure 36: The three robots used for the video based trials

Applied to the present study, the method consisted of creating three video recordings which I edited to provide three videos of exactly the same scenario, but each using a different robot. The three videos were filmed in the 'Robot House', described previously in Chapter 4.1. The three robots (Figure 36) were designed to exhibit appearances which ranged from Mechanoid to Humanoid. The robots' static appearances (from photographs) were rated on an appearance scale by a panel comprised of 26 researchers from various disciplines including physics, computer science, astronomy and various administrative staff at the University. The scale ranged from very Mechanoid (1) to very human-looking (20). Figure 37 shows the mean ratings for each robot, the corresponding standard errors and the 95% confidence interval bands. A Friedman non-parametric ANOVA rated the results as highly significant (Chi Sq. (N = 27, df = 2) = 44.78431 $p < .00001$). In most cases, the ranking order of the robots was the same and the three robots were labelled according to their mean rating values for static appearance: Mechanoid (mean = 3.67), Basic (mean = 6.63) and Humanoid (mean = 12.22). Note that these names are simply used as labels to distinguish the three robots from each other, as none looked particularly human-like in appearance (cf. Chapter 1 for the working definitions of mechanoid and humanoid robots used in this text). The robots' static appearance (as judged by the panel from photographs) was not the same as the robots' appearance experienced by the participants in the VHRI trial. The robots in the trial videos were moving and the perceived robot appearance could therefore be considered to be *dynamic appearance* (that is, robot appearance including and also affected by the behaviour(s) of the robot). Thus, the *dynamic appearance rating* is effectively an assessment of the robot as a whole; including not just the robot's static appearance but also includes any movements or other robot behaviours and expressions observed.

For creating the videos of the three scenarios, each robot displayed a repertoire of attention seeking cues and behaviours corresponding to their respective robot features. Three different attention-seeking mechanisms were used: manipulator movement, lights, and sound. The manipulators differed between the three robots: The Mechanoid robot was fitted with a simple one Degree of Freedom (DoF) gripper which was able to move up or down only. The Basic robot had a simple (one DoF) arm fitted with a compound movement which allowed the robot to lift the arm and make a pointing gesture. The Humanoid was fitted with two arms each of seven DoF and was able to make a more human-like waving gesture.

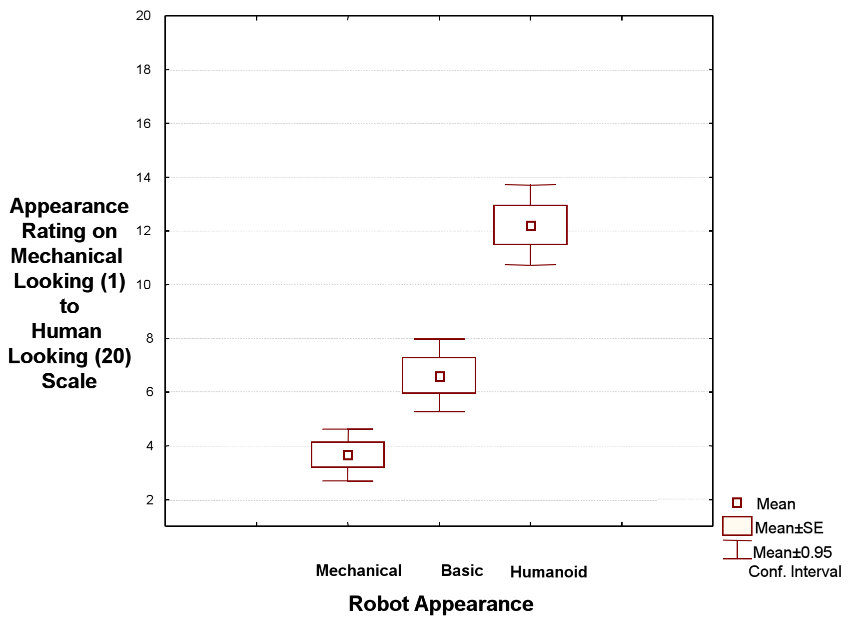


Figure 37: Panel ratings of the robot static appearances on the mechanical-human appearance scale.

Note that it is impossible for either the lifting or pointing arms to make a waving gesture, and conversely, the human-like arms could not easily make a simple lifting or pointing gesture comparable to the actuators of the two other robots. In addition to the movement of the manipulator, visual cues were used as attention-attracting mechanisms: The Mechanoid robot was equipped with a pan and tilt camera unit, fitted with a single flashing light. The Basic robot had a simple head with two flashing lights in place of eyes, and the Humanoid robot had multiple flashing lights in the place of mouth and eyes. Each robot also provided a sound. In the case of the Mechanoid robot, a series of two beeps was used. The Basic robot used a poor quality synthesized voice. A high quality recorded male human voice was used for the Humanoid Robot. For both synthesized and human voice, the speech content was identical and consisted of the phrase "There is someone at the door." These various attributes to be tested for each of the three robots were therefore categorized as: (dynamic) appearance, gesture, light signal, and sound signal.

It should be noted that the appearance and (attention-seeking) behaviour of the robots could not be studied independently in different conditions due to the embodied nature of the robots. For example, if a robot with 'humanoid appearance' speaks with a mechanical voice then it violates the consistency of peoples perception of that robot's appearance and behaviour: it will no longer be the 'humanoid' robot that people are judging, but 'something else'. This 'holistic' nature of dynamic robot appearance does not allow a clear decomposition of different robot appearance and behaviour features, an approach actually required to perform valid statistical analyses on the different independent features. This exemplifies one of the many methodological challenges that human-robot interaction researchers are faced with.

At the beginning of each trial an introduction video was shown to the participants that included background information about the work of the research group, the purpose of the current trial and detailed instructions for participating in the experiment. As these instructions were recorded, consistency in administering the tests was enhanced. An experiment supervisor was on hand to answer any further questions and to repeat the instructions if necessary. After the introductory video was played, the main trial videos were shown to the participants. The trial videos followed the same scenario which consisted of the following sequence of scenes:

1) A person is shown relaxing on a sofa in the living room and listening to loud music. (Figure 38a)

2) A visitor approaches the front door and rings the doorbell. (Figure 38b)

3) The robot (Mechanical, Basic or Humanoid for each of the three videos) responds to the doorbell, and then acts as if it had assumed that the human has not heard it. (Figure 38c)

4) The robot enters the living room and approaches the human. This part of the scenario was shown as viewed from the position of a third party. (Figure 38d)

5) The video then switches to the viewpoint of the human (on the sofa), looking directly at the robot. The robot then performs its respective attention seeking behaviours to indicate that a human response is required: light signal, gesture and sound signal. (Figure 38e)

6) The human is then seen following the robot out of the room, and then opening the door for his visitor. (Figure 38f)

The three videos were shown to a total of 79 undergraduate students, in three separate group sessions ranging in size from 20 – 30 individuals at a time. The participants filled in the questionnaires individually. Generally, in order to reduce social facilitation effects (cf. Woods et al. (2005)), the group sessions did not involve any discussion of the main trial videos and how participants rated the different robots.

Figure 38: Cut Scenes Illustrating the Three Videos used for the Study. The person is listening to music a), when a visitor arrives b). The robot(s) hears doorbell c), and signal to the person that he has a visitor d) and e). He answers the door f).

The participants signed consent forms, provided basic demographic details including, background, gender, handedness and age, before they were exposed to the introductory video. They were then shown the three main trial videos, each group in a different order, of a robot attracting attention from a person – featuring the Mechanical, Basic and Humanoid robots. After the three videos were displayed, a slide showing the three robots (Fig. 36) with their names and features was projected on the main screen as an aid to participants' memory as to the identity of the robots in the videos. The participants were then asked to fill in a questionnaire in order to collect their opinions and preferences towards the three robots and the various attention seeking behaviours. Details of the relevant questions from the questionnaire are provided below in the Results and Analyses section. For each session, the three robot scenario videos were presented in a different order. As there were only three group video sessions, not all possible permutations of video presentation order could be covered.

5.2.2 RABE Findings

Typically, when carrying out a study of this type the various features involved (in this case appearance, sounds, flashing lights and manipulator gestures) would be isolated into a number of separate conditions and a series of tests performed with the various permutations of conditions in order to achieve statistically valid results. However, it was not possible to perform this type of study using robots since the various features of a robot (e.g. appearance, manipulator type, head type, speech or sounds etc.) cannot be isolated from each other. For example, only a robot with a human-like arm will physically be able to perform human-like gestures. Also, each particular robot (e.g. a particular 'Humanoid robot' or "Mechanoid robot') has an overall appearance which is different than the sum of its individual parts. If any one part or behaviour is changed, effectively this will create a different robot. If individual robot component parts and behaviours were examined in isolation (even in cases where this were possible, e.g. varying a robot's speech), the concept of a 'robot' would be lost. It is not advisable to consider any one aspect of a robot (such as a particular gesture, speech quality, sound or any other parts or behaviour) in isolation from the rest of the component parts and behaviours which together make up the complete robot. Therefore, it was not possible to fully isolate and cross combine the various appearance and attention seeking behaviours as the robot features tested were not truly independent.

For analysis purposes, it was assumed that dynamic robot appearance would be closest to an independent variable. The other attention seeking behaviours would then be perceived by the human test participants as either being consistent or inconsistent with the overall dynamic appearance of each robot. To measure this, each participant provided a set of ratings on a Likert scale (1 = Dislike a Lot, 3 = Neutral, 5 = Like a Lot) for their preference for each robot's (dynamic) appearance, light signal, sound signal and gesture behaviour. For example the Mechanoid robot exhibited a single flashing light, a beep sound and a simple lifting gripper gesture. Participants rated their preference for dynamic appearance and these three attention seeking behaviours for the Mechanical robot. In the same way the preference ratings for the twin flashing lights, the low quality synthesized voice and the pointing arm gesture were obtained for the Basic robot. The multiple flashing eye and mouth lights, the high quality (recorded) human voice and the waving arm gesture were likewise rated for the Humanoid robot. Friedman non-parametric ANOVA for repeated measurements were performed on all the participant's ratings.

5.2.2.1 Robot Appearance Ratings

Highly significant differences were found for the dynamic appearance scores (Chi Sq. = 33.10425, N=76, DoF=2, $p < .000001$). The mean results are illustrated in Figure 39, along with a visual indication of standard error and 95% confidence interval bands. In general, the participant's ratings of robot dynamic appearance indicated that they preferred the Humanoid robot overall, followed by the Basic robot and finally the Mechanoid robot.

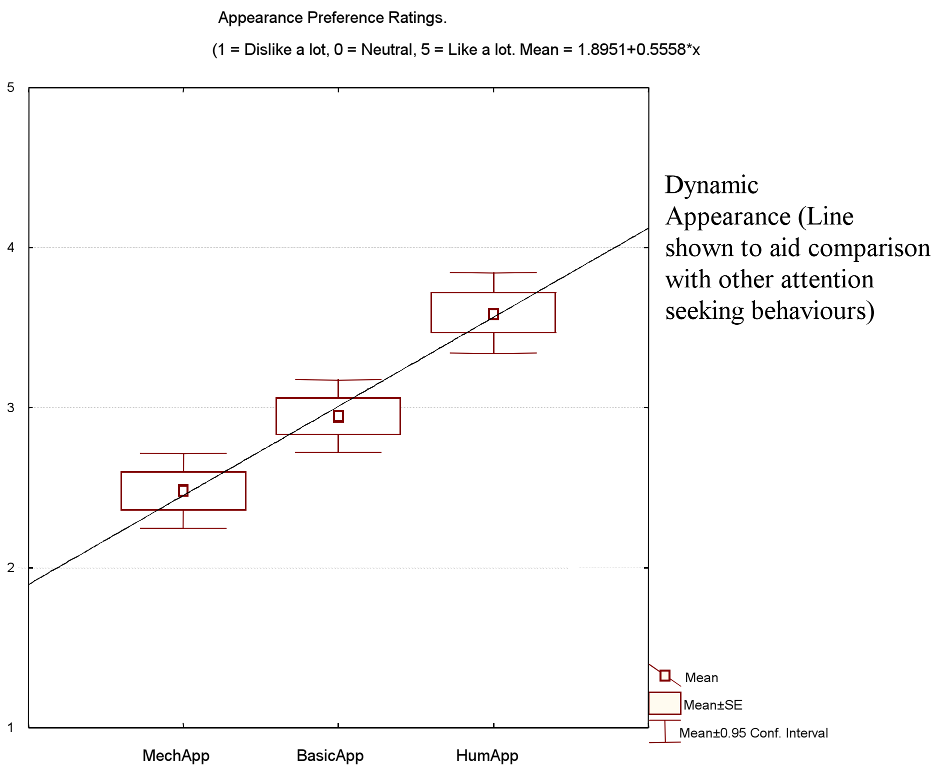


Figure 39: Participants' mean appearance ratings for the three robots.

5.2.2.2 Robot Attention Seeking Behaviours

The three sets of attention seeking behaviour employed by the three robots were not truly independent from each other, or from the respective robots' appearances. However, as argued previously, the different dynamic appearances of the three robots can be considered to encapsulate the main overall impression of an individual robot by each trial participant. We therefore used the robot's (dynamic) appearance rating as a base line for gauging the contribution of each of the individual attention seeking behaviours. For this purpose the line marking the best linear fit of the mean appearance preference ratings was drawn (see Fig. 5). (Note that this line only acts as a visual guide to allow easy comparison with the other attention seeking behaviours. Because the order of the three robot types along the horizontal axis is at most ordinal, no conclusions should be drawn about the shape of this line per se).

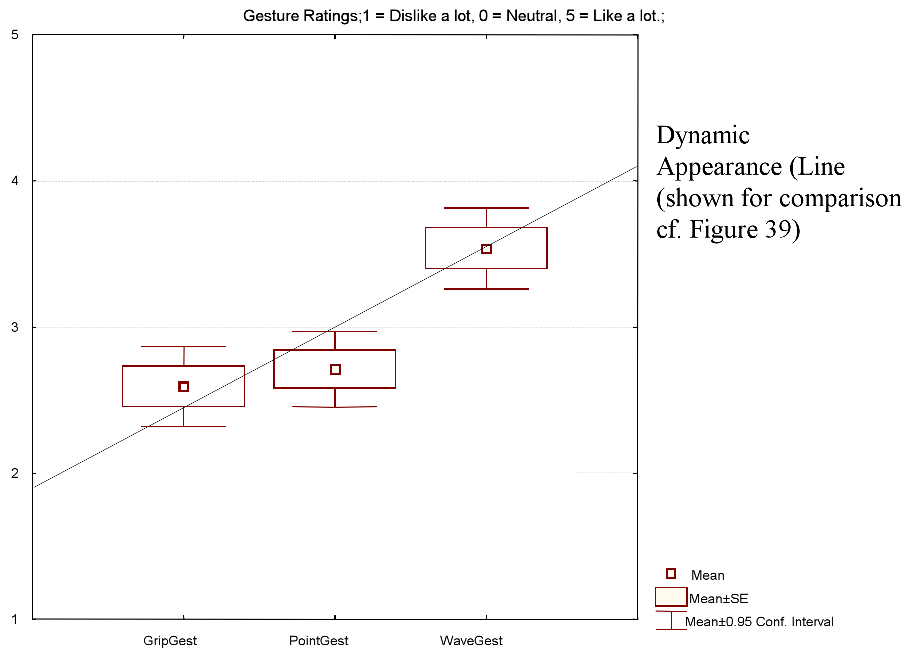


Figure 40: Ratings of the robots' gestures

It can be seen that when compared to the means obtained from the overall appearance ratings, the Humanoid robot's waving gesture is rated similar to the same mean value as dynamic appearance. For the other two robots, the mean for the lifting gripper gesture is rated better than the overall Mechanical robot appearance rating, and the pointing gesture is rated less then the Basic robot appearance rating (Figure 40). The differences in rating between the gestures of the three robot types were highly significant by the Friedman test (Chi Sq. =25.73799, N=76, df=2, p< .000001).

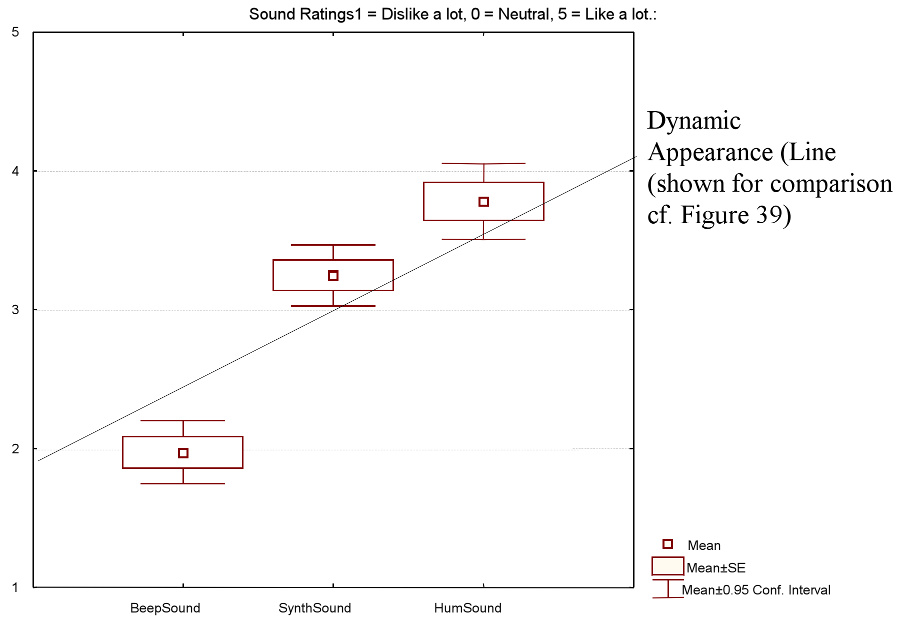


Figure 41: Ratings of the robots' sounds

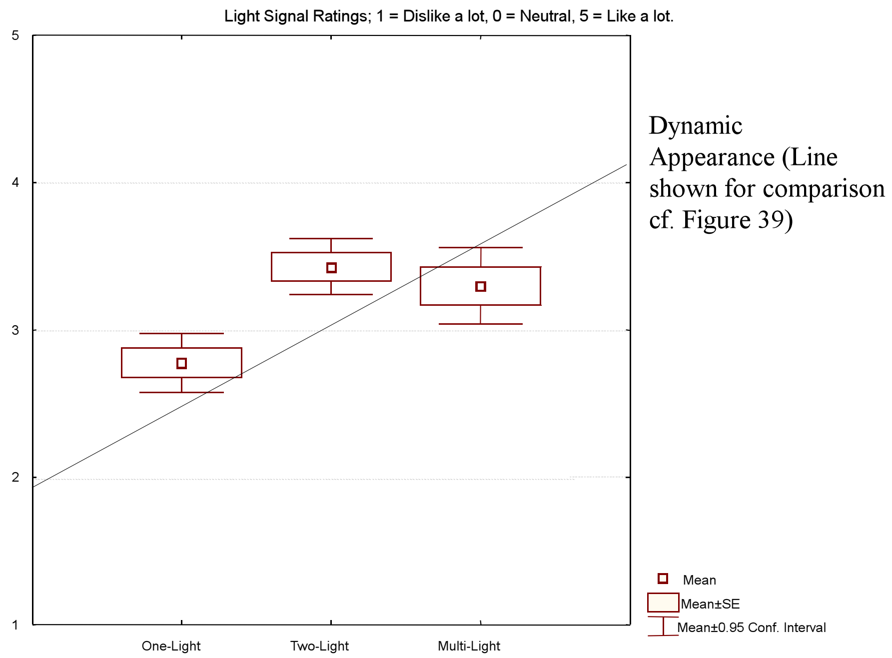


Figure 42: Ratings of the robots' light signals

The differences between the ratings of the light signal and sound signal were highly significant. (Sound signal; Chi Sq. = 62.86, N = 77, df =2, p < .000001; Light signal; Chi Sq. = .25.74, N=76, df =2, p < .000001.). (Figures 41 and 42) For the light signals, the single light of the mechanical robot and the two light of the basic robot were better liked than their respective appearance ratings. The multiple flashing lights on the Humanoid robot, however, were rated as less liked than the overall dynamic appearance rating might suggest (Figure 42). It can also be seen that speech is generally liked better than simple beeps, and that speech tends to be more highly rated than the appearance ratings might suggest, and the beeps were rated a comparatively less liked than the mechanoid robot (overall) appearances.

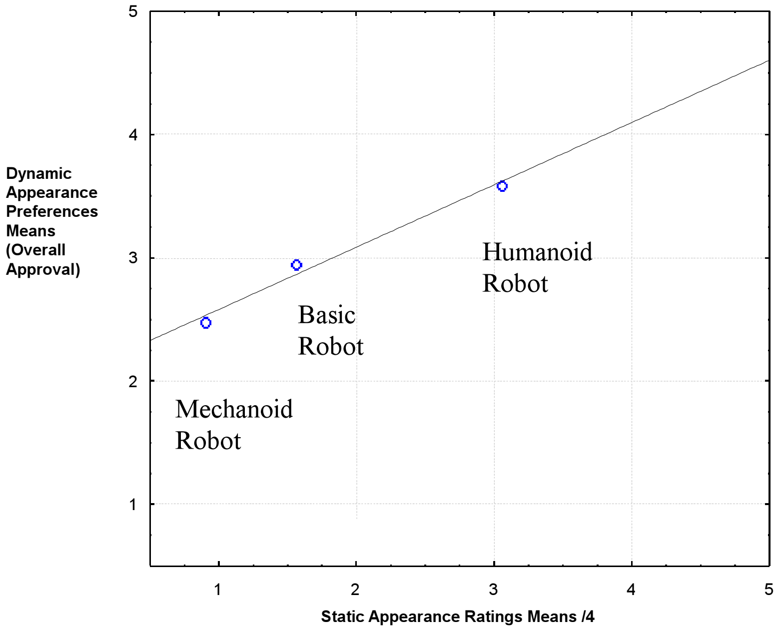


Figure 43: Robot static appearance ratings vs. robot dynamic appearance preferences

5.2.3 RABE Discussion and Conclusions

In all the findings above, any Likert value below 3 implies that a feature or behaviour was disliked. Any value above 3 indicates that a feature was liked overall. The Basic robots attributes were all close to the neutral value of 3, implying that overall it was not particularly liked or disliked. The Mechanical robot's attributes consistently fell into the category below 3 indicating that overall it was mildly disliked. Other interesting observations are that speech, even of poor quality, is liked in contrast to simple beeping sounds which are disliked. Overall, it can be seen that the Humanoid robot's appearance and behaviours were all liked to some degree. However, the multiple flashing eye and mouth lights feature were not liked to the same degree as the rest of the Humanoid robot's attributes and were actually rated as less liked overall than the twin flashing lights on the Basic robot. The left hand side of Mori's original diagram (cf. Chapter 2) illustrates his idea that humans are more approving of robots which have more human-like appearance and behaviour (up to a certain point). It is interesting here to plot the panel ratings (from Figure 37), which were purely judging robot static appearances on a mechanical to human-like looking scale, against the actual dynamic appearance preference ratings of the HRI trial participants (Figure 43). The independent panel's ratings on the mechanical-human appearance scale means (range 1 to 20) were divided by 4 in order to show them on the same 5 point scale as those for the trial participant's dynamic appearance ratings.

Figure 43 highlights that the ratings for the robots, for both static and dynamic appearance, increase from Mechanoid to Basic to Humanoid robot, thus providing support for the left hand side of Mori's diagram. There are insufficient data points (and it would be questionable anyhow because the dynamic appearance ratings are based on a Likert scale which is only ordinal) to show if the relationship between increasing human-like appearance and human approval is actually linear or some other functional relationship.

The labelling of the robot types (Mechanical, Basic, and Humanoid) in the videos and instruction slides shown to the participants could be open to critique, because it might have influenced their judgements. However, the various attributes of each robot were rated separately by participants. That the flashing lights of the "Humanoid" robot were not actually liked as much as the overall appearance of the robot suggests that participants were not unduly influenced by the names used for the three robots. However, future trials should avoid the use of leading names for any robots rated by trial participants.

These findings have implications for the designers of robots which must interact with humans. Where a robot behaviour or feature is rated by humans as less liked or approved of than a robot's overall appearance might suggest, there will inevitably be a degree of disappointment. This may explain why humans become rapidly discontented with toys and robots which have a very interesting and anthropomorphic visual appearance, but prove to be disappointing after actual interaction takes place.

The number and range of robots tested in this study is not large enough to provide statistical evidence to support the whole of Mori's diagram as none of the robots had an appearance which was human-like enough to trigger the uncanny valley effect. The results obtained here can only be taken as evidence to support the left hand side of Mori's diagram. More experiments using finer gradations of robot appearances and behaviour are required to provide more extensive evidence, to give more data sample points and to refine the parameters which govern human perception of robot appearance and behaviour. However, the methods developed and used here, and the results gained have yielded useful insights into how to calibrate robot appearance and behaviour so that owners and users of domestic or companion robots in future will be less disaffected due to design feature limitations which do not live up to their initial expectations.

5.3 Chapter Summary

This section presents the results of video based Human Robot Interaction (HRI) trials which investigated people's perceptions of different robot appearances and associated attention seeking features and behaviours displayed by the robot. The methodological approach highlights the holistic and embodied nature of robot appearance and behaviour. Results indicate that people tend to rate a particular behaviour less favourably when the behaviour is not consistent with the robot's appearance. It is shown how participants' ratings of robot dynamic appearance are influenced by the robot's behaviour. Relating participants' dynamic appearance ratings of individual robots to independently rated static appearance provides support for the left hand side of Mori's proposed "uncanny valley" diagram. I exemplify how to rate individual elements of a particular robot's behaviour and then assess the contribution of those elements to the overall perception of the robot by people. Suggestions for future work have been outlined.

5.4 Responsibility for Work Performed

This RABE VHRI trial was devised, set-up and carried out with help from my colleagues, Kheng Lee Koay, and Sarah Woods. The trial questionnaires were managed overall by Sarah Woods, who included the questions relevant to this study on participant ratings of robot appearance at my request. The statistical analysis on these particular questionnaire results was carried out by myself. The findings have been presented in Walters et al. (2007d). An article based on findings from the study has also been accepted for journal publication (cf. Walters et al. (2008a)). Other findings and outcomes from the study relating to participants personalities and preferences can also be found in Syrdal et al. (2007).

As the team member with mechanical, control and robotics experience, I developed most of the robot and HRI trial systems hardware. I designed, developed, constructed and programmed both the humanoid arms and the humanoid head for the PeopleBot™ robots (cf. Appendices I and II) which were used to create the humanoid robot appearance and associated behaviour and gestures for the trial videos. Kheng Lee Koay designed and built the Basic Robot head. I also directed and filmed the trial videos with help from Kheng Lee Koay, and our colleague Wan Ching Ho who acted as the human participant in the videos.

Chapter 6: Multiple Factor HRI Trials

This Chapter presents findings from a Live Multiple Factor Experiment (LMFE), which was carried out to investigate interaction effects between RH approach distances, robot appearances and robot behaviour for human preferences and perceptions as part of a large scale series of live HRI trials.

In Chapter 3, the findings from exploratory HRI trials were presented which indicated that Hall's social spatial zones are broad categories and HR approach distances can be affected in more complex ways by aspects of robot non-verbal behaviour. In these previous human-robot comfortable approach distance experiments it was found that most participants approached a mechanoid robot to distances that lie within the closer part of Hall's Personal Zone, reserved for conversation between friends (cf. Walters et al. (2005a), Walters et al. (2007)). In the third PRVE trial (cf. Walters et al. (2008)) investigating comfortable human approach distances to a mechanoid robot which used four different voice style there were no significant differences found for comfortable approach distances for humans that had experienced a short previous interaction with a similar robot. However, non-habituated humans tended to approach a mechanoid robot with a either synthesized or female voices to further (comfortable) approach distances than to a robot with a male or no voice. A possible reason advanced for these initially greater approach distances was that they were due to inconsistencies between participants initial expectations for robot appearance and robot voice.

Butler & Agah (2001) explored the psychological effects of interactions between humans and mobile personal robots under conditions of different robot speeds, approach distances, and robot body design. Their experimental contexts included the robot approaching and avoiding a human, both while passing by and also performing non-interactive tasks in the same area as a human. Only direct, direct fast and indirect frontal approaches were considered. Two robot appearances were used; a tall (1.7m high with a simple head and arms, and a wheeled base) humanoid robot and a short (0.35m high, cylindrical and wheeled)) mechanoid robot. Findings indicated that generally participants preferred closer (comfortable) approach distances by a short (0.35m) mechanoid appearance robot than by the tall humanoid robot. Fast approaches (approx. 1m/s) by the tall humanoid robot in particular caused uncomfortable feelings in the human participants.

Our previous HRI proximity trials have investigated robot to human approach distances for mechanoid appearance robots only. In the Butler & Agah (2001) study, only a tall humanoid robot and a short mechanoid robot was used. Findings from HRI trials by others (cf. Chapter 2) and myself (cf. Chapter 5), investigating effects of robot appearance on users perceptions and expectations, indicate that people tended to rate particular behaviors or features less favourably when they are not perceived as consistent with the robot's overall appearance.

The current study was performed as part of a larger series of HRI trials which took place in the University of Hertfordshire "Robot House" in Summer 2006. This set of LMFE HRI trials incorporated a number of experiments specifically to investigate issues of robot appearances, task context and situation, humans' preferences and perceptions for robot appearance and behaviour, and notions of robot autonomy and control. This trial series was the most complex we had run to date, both in terms of the number of variables and experimental conditions under investigation, and also in the number of separate experiments carried out.

Many of the findings from these LMFE HRI trials relevant to this study have been submitted for publication in Walters et al. (2008a). Other aspects of the trials outcomes have also been reported in Syrdal et al. (2007a) where findings indicate differences in approach direction preferences based on gender, and that participants' personality traits of extroversion and conscientiousness are associated with closer robot approach distance preference ratings, and differing perceptions and preferences for robot autonomy. Also in Koay et al. (2007b) which investigated how participants' opinions and preferences changed over time as the participants habituated to the robot over a period of five weeks. These results show that preference ratings for robot approach direction and robot appearance changed over time, and that participants who are accustomed to the robot tend to prefer to be more 'in control' of the situation - in that they appreciated reduced robot autonomy in case of unexpected events.

The part of the trials, running between the second and fourth weeks primarily to habituate the long term participants to the robots, also allowed the opportunity to carry out a number of more exploratory experiments into different aspects of human and robot co-habituation. These aspects also included investigations into how participants own personality factors influences their preferences and perceptions of the four robots, analysis of the participants views on task domains, capabilities and abilities of the four robots. The results and data obtained from this series of exploratory trials are not central to the main theme of this study and therefore will not be reported in this thesis.

6.1 Further Robot and Trial Systems Developments

Figure 44: A comparison of the tall and shortened versions (right, with humanoid head) of the PeopleBot™ robot.

One of the proposed controlled conditions for the trial was robot height, in order to investigate the effect of different robot heights on peoples perception of the robot. It was necessary therefore to carry out hardware modifications on one of the PeopleBot™ robots to create a shortened version. I achieved this by stripping down the robot to its component parts and cutting a 200mm section from both of the robot's side panels and side support plates. There was a lot of empty space in these side supports, and there was room to relay the wiring in the side channels back up to the top section of the robot as they were before. I replaced the lifting gripper track with a shorter length of 1" square tube and shortened the gripper drive belt. However, I made the changes in such a way so that in future the robot can be easily restored to its original size and configuration. The resultant difference in height between the shortened and standard versions of the PeopleBot™ is illustrated in Figure 44. It was estimated that when approaching a seated person the short robots (humanoid) head or pan and tilt camera unit would be approximately at the same level or slightly lower than an average seated persons eye level.

My colleague, Kheng Lee Koay integrated the CLD signal receiver into the on-board PeopleBot™ robots sonar and a laser ranging systems, so that the the distance to the participant was automatically measured and logged when the the CLD button was pressed. The on-board IR laser range sensor datum is set back 10cm from the front edge of the robot so the raw distances obtained were adjusted accordingly so that they were directly comparable to those obtained from previous HR proxemic studies (cf. Chapter 3)

6.2 Live Multiple Factor Experiment (LMFE)

The main HRI trial series ran over five weeks with a main purpose of investigating how a group of long term participants preferences and responses towards robots changed over that period. The main instrument to assess participants over the period was a controlled set of experiments which measured participants ratings, responses and comfortable approach distance preferences towards a personal companion robot under a number of experimental conditions. The conditions which were controlled were robot appearance, robot height, task context, notions and perceptions of robot autonomy, and approach direction. In the case of the long term group their responses and preferences were tracked over five week period of habituation with the controlled set of trials repeated during the first, second and fifth week of the trial period. A greater number of short term participants underwent a controlled test series over the short term to establish a firm statistical baseline for comparison with the repeated test observations from the long term participants.

The aim of these studies was not to provoke Mori's "uncanny valley" repulsive effect (cf. Mori (1970) and MacDorman (2005)), but to investigate the observation that increasing the human-likeness of robots, but not to the extent that the repulsive effect was invoked, would improve users interaction experience and effectiveness (cf. Goetz et al. (2003) and Minato et al. (2004a)). As none of the robots used in the study were particularly human-like, it was expected that the participants would generally prefer one of the "humanoid" appearance robots. The robot height condition was incorporated in the HRI trials to investigate the notion that a shorter robot would be less intimidating and would therefore be allowed to approach closer than a taller robot. The findings for these trials reported previously in Syrdal et al. (2007a) indicated a general effect for mechanoid/humanoid robot appearance, whereby participants overall allowed a mechanoid appearance robot to approach more closely than the humanoid appearance robots. These findings also indicated that there were only significant differences in approach distance related to robot appearance. It was anticipated therefore, that possibly *participants expressed preferences* for robot appearance may possibly have effects on participants preferred robot approach distances, but *robot height preferences* would not have any effects. Three hypotheses were advanced for testing:

1. *Participants will have a general overall preference for one optimal combination of robot appearance and height, based on their perception of robot attributes for height and appearance*

2. *Participants* ***preferences*** *for a tall or short robot will have an effect on their actual comfortable robot to human approach distance*

3. *Participants* ***preferences*** *for a mechanoid or humanoid robot appearance will have an effect on their actual comfortable robot to human approach distances.*

6.3 LMFE Trial Method and Procedure

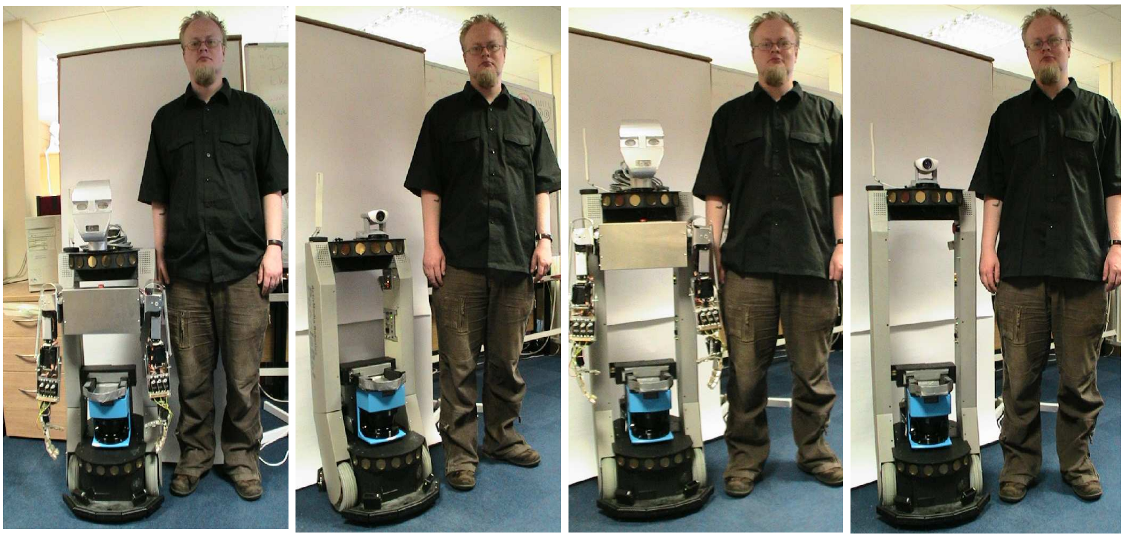
These LMFE HRI trials took place in the same “Robot house” as in the previous Main Study VHRI and RABE HRI trial videos (cf. Chapters 4 and 5, Dautenhahn et al. (2006), Woods et al. (2006a) & Koay et al. (2007)). The main instruments of this study were participants responses to specific post trial questions, administered by questionnaires, in conjunction with robot to human comfortable approach distance data. The comfortable approach distance findings have been reported in conjunction with participants personality data in Syrdal et al. (2007a) and in conjunction with longitudinal habituation findings in Koay et al. (2007b).

6.3.1 LMFE Trial Participants

There were 33 participants who carried out the LMFE RH approach trials on a first exposure basis. From this sample, there were 12 Long Term participants, who subsequently went on to carry out these LMFE approach trials a further two times over a five week period as part of a separate experiment to investigate changes in RH approach preferences over and extended period of habituation to the robots. The final questionnaire response data, which is the focus of this study was gained from each participant after their initial LMFE HRI trial was completed. The participants were drawn from the University population and were mainly postgraduate students, one academic staff member and a one undergraduate student. Their ages ranged from 21 to 50 and there were 20 males, 13 females overall. From this group, 8 males and 4 females formed the long term group.

6.3.2 Robots Types Used in the LMFE Trial

Four robot types were used for the HRI trials and differed only in the combination of two controlled factors. The robots were carefully designed (using commercially available PeopleBotsTM robots as a common robot platform) to be the same in appearance and behavior apart from the one appearance factor (mechanoid or humanoid) and one for height (Short = 1.2m, Tall = 1.4m). In order to see which of height, appearance or both factors influenced participants preferences and ratings of robot behaviour ratings and comfortable approach distances, a 2x2 combination of Tall vs. Short and Mechanoid vs. Humanoid robot appearances were used in the trials (see Figure 45). All participants completed post trial questionnaires where they were asked for their preferences and opinions with regard to all four possible robot appearances and heights. Note; none of the robots used were particularly human-like in appearance. They are simply used as labels in this text here as a shorthand to distinguish easily the main design features of the four robots (cf. Chapter 1 for working definitions of Humanoid and Mechanoid used here).



Robot A *Robot B* *Robot C* *Robot D*

Figure 45: The PeopleBot™ Robots used for the HRI Studies: A) Short Mechanoid, B) Short Humanoid, C) Tall Mechanoid and D) Tall Humanoid.

Robot A was 1.2m tall and mechanical looking ("Short Mechanoid"), B was 1.2m tall and had a simple metallic head and two metallic human-like arms ("Short Humanoid"). C and D were both 1.4m tall, with C having mechanical features ("Tall Mechanoid") and D the same human-like features as B ("Tall Humanoid"). The terms "mechanoid" and "humanoid" were not used to participants in the HRI trials or in questionnaires; The robots were simply referred to as Robots A, B, C or D (see Figure 45). All participants underwent the same controlled experiment with only one of the four robots types. The robot type actually used was assigned to each participant in sequence, so that approximately the same numbers experienced each robot type. (N=33; A, n=8; B, n=8; C, n=8; D, n=9).

6.3.3 LMFE Trial Test Conditions

The participants used the CLD, as in previous live HRI trials (cf. Chapter 5), to signal when the robot had approached to a distance which they found comfortable for each trial run. If a participant did not operate the CLD, the closest approach distance of the robot was recorded for the particular trial run. To explore how the level of robot autonomy affected their comfortable approach distance, the CLD had two modes of operation which corresponded to the conditions Human in Control (HiC) and Robot in Control (RiC). Under the HiC condition, a press of the CLD button caused the robot stop advancing towards the participants. Under the RiC condition, a press of the CLD button did not affect the robot's advance, and it carried on until the robot pre-programmed safety distance was triggered. In both cases the robot recorded the actual distance to the human, using the robot's internal laser range sensing system, when the CLD button was pressed. For each of the two robot autonomy conditions, three different task context conditions were studied;

No Interaction - where the robot approaches participants as incidental to carrying out a task not involving the human.

Verbal Interaction - where the robot approaches participants in order to speak commands to the robot.

Physical Interaction - where the robot approaches the human for a joint task which required physical contact with the human.

Table 8: The Experimental Conditions for Main HRI Trial Series

Robot Autonomy	**Interaction Context (P, V, and N) x Approach Direction (Front, Front Right)**		
	Physical	*Verbal*	*None*
Robot in Control (RiC)	Front Front Right	Front Front Right	Front Front Right
Human in Control (HiC)	Front Front Right	Front Front Right	Front Front Right

For each of the Interaction conditions, approaches were made from the front direct, and from the front right side quarter. Table 8 shows the experimental conditions matrix of 2 (Autonomy) x 3 (Interaction Contexts) x 2 (Approach Directions). Figure 46 illustrates the trial procedure with pictures showing a typical robot approach.

Figure 46: The HRI Trial showing the robot approaching a seated participant from her front right direction. Note the 0.25m grid overlay and the CLD light signal (arrowed).

The main findings published by my colleagues, Kheng Lee Koay and Dag Sverre Syrdal, relevant to this study are briefly summarized here. More details related to these particular LMFE HRI trials findings can be found in Koay et al. (2007b) and Syrdal et al. (2007a).Significant differences in comfortable approach distances found during the live HRI trials were for the Interaction context conditions. Participants allowed all robots to approach more closely during Physical Interactions, and preferred more distant approaches during Verbal and No Interaction conditions (Table 9).

Table 9: RH Approach Distances vs. Interaction Context (cf. Koay et al. (2007b))

Approach Context	**Mean(mm)**	**Standard Error (mm)**	**95% Confidence Interval (mm)**	
			Lower Bound	*Upper Bound*
No Interaction	602	13.055	575.957	627.303
Verbal Interaction	605	13.055	579.557	630.903
Physical Interaction	488	13.055	462.798	514.144

Significant effects on comfortable approach distance were also found for the appearance (mechanoid or humanoid) of the robot experienced by participants, but none related to the actual height of the robot (short = 1.2m, tall = 1.4m). In general, people preferred the humanoid appearance robots (B and D) to keep a further distance away than the mechanical robots (A and C) (see Table 10).

Table 10: RH Approach Distances vs. Robot Appearance (cf. Syrdal et al. (2007))

Robot Appearance	**Mean**	**Standard Error**	**95% Confidence Interval**	
			Lower Bound	*Upper Bound*
Mechanoid	508.456	10.830	487.158	529.753
Humanoid	621.766	10.486	601.145	642.387

For the purposes of the present study, a mean comfortable RH approach distance was calculated for each participant over all the experimental conditions for Autonomy, Approach Direction and Interaction for the week one (first exposure) results only. The post trial questionnaires were administered to participants and contained questions relating to participants overall opinions, perceptions and preferences with regard to all four robot types from static photographs (see Figure 45). The four robot types (A, B, C or D) shown to them also included the one robot type which they had previously encountered in their live trials. There were two questions relevant to this study relating to:

Personal preference ***choices*** *as to most and least liked robot types* .

Personal ***ratings*** *for the degree of liking each robot using Likert scales.*

Note the questionnaires also included questions on the participants own personality and ratings of the robots' personalities, human-likeness and intelligence, and also to investigate participants views as to suitable task domains for each of the four robot types. These latter categories were not relevant to this study. The questions were broadly categorised into three types which required the participants to respond in three possible ways:

Qualitative response - Participants provided a short sentence with an individual and descriptive response. (E.g. "Give reasons for why you liked this robot the most?"). These results can be grouped by main responses, terms and themes and the respective frequencies examined to provide overall qualitative impressions. These questionnaire results are not relevant to this thesis and are not considered here.

Overall preference - a multiple choice selection response was presented (E.g. : "Which was your most preferred robot? Choose answer from: A, B , C or D:"). These nominal answers were used as grouping factors for a GLM (General Linear Model) Univariate ANOVA for significant differences between groups for mean comfortable approach distances (scale data).

Quantitative ordinal ratings - Used a five point Likert scale to obtain ratings (e.g. "How much did you like robot A?" Response from: 1 = Not at all, 2 = Not much, 3 = Neutral, 4 = A bit, 5 = A lot). These were compared with each other by non-parametric tests to obtain significant differences and correlations. Friedman ANOVA tests were used to test for significant differences between Likert scale answers and Spearman's Rho tests for significant correlations. The relevant results are considered in the sections below:

6.4 LMFE Trial Findings

6.4.1 Most Preferred Robot Type.

The robot types which were preferred by the participants showed a significant ($\chi 2 = 10.254$, df = 3, p = 0.017??) bias towards preferring the tall humanoid (Robot D, n=7, 36.8%), and the short mechanoid types (Robot A, n=6, 31.6%) followed by C (n =4, 21.1%) and B (n = 2, 10.5%) (Figures 47). Participants preferences indicated no significance for both robot height ($\chi 2 = 0.290$, df =1, p = 0.590) and appearance ($\chi 2 = 0.290$, df =1, p=0.590). It must be therefore assumed that the reasons for a particular robot type (A, B, C or D) being preferred by individual participants were based on individual or internal factors.

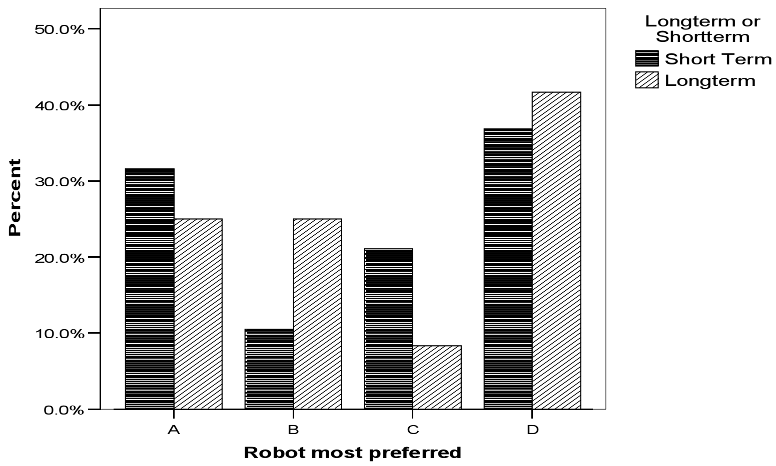


Figure 47: Most preferred robot types for single exposure and long term exposure participants. A = Short Mechanoid, B = Short Humanoid, C = Tall Mechanoid and D = Tall Humanoid

Non-parametric cross tabulation results (Cramers Phi = 0.296, p = 0.975) also indicated there were no correlations between the robot types which short-term participants encountered in their HRI trials and their preferred robot types. It seems therefore, that previous trial exposure to a particular robot type did not affect any participants preference for a particular robot type in any direct ways.

Participants also provided a Likert scale based rating of how much they liked each of the robot types. Spearman's Rho tests found significant positive correlations between participants liking for robot A and liking for robot C ($r = .532$, $p=.002$), also between liking robot B and liking D ($r = .609$, $p<.001$). There was also a negative correlation between a liking for robot A and a disliking of robot D ($r = -.366$, $p = .043$). The common factor to these correlations is robot appearance. Individuals tend to like both the robots (B and D) with humanoid appearance, or like both the robots with mechanoid appearance (A and C). This was reinforced by a significant correlation between a preference for mechanical appearance and liking of robot A ($r = -.679$, $p = .001$) and a correlation between a preference for humanoid appearance and liking of robot D ($r =.619$, $p = .005$). There were no significant correlations between the robot overall ratings and robot height, indicating that robot height did not have a major effect on participants preferences for a particular robot type. Participants also rated the for degree of human-likeness, and Spearman Rho correlation tests found a significant result for liking the tall humanoid robot (D) and rating it as more human-like ($r = -.449$, $p = .013$). There was also a correlation for liking the small humanoid robot (B) and rating the tall mechanoid robot (C) as more human-like ($r = -.0382$, $p = .037$). This result is surprising, but indicates that participants who overall preferred the small humanoid robot (B) also seemed to think that the tall robot mechanoid (C) also had one or more attributes that were perceived as human-like. The implication is that the tall factor also reinforces the perception of human-likeness. This notion is supported in that tall humanoid robot (D) was perceived as slightly more human-like than small humanoid robot (B) (Figure 49).

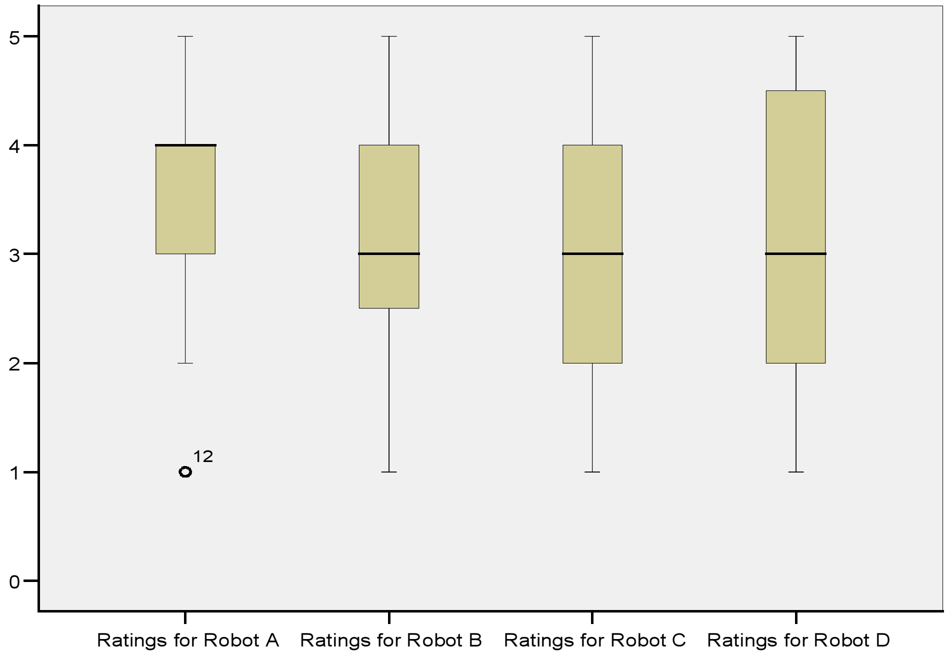


Figure 48: Mean participants ratings of robot types (A, B, C, and D) on a five point Likert Scale (1 = Like not at all , 5 = Like very much).

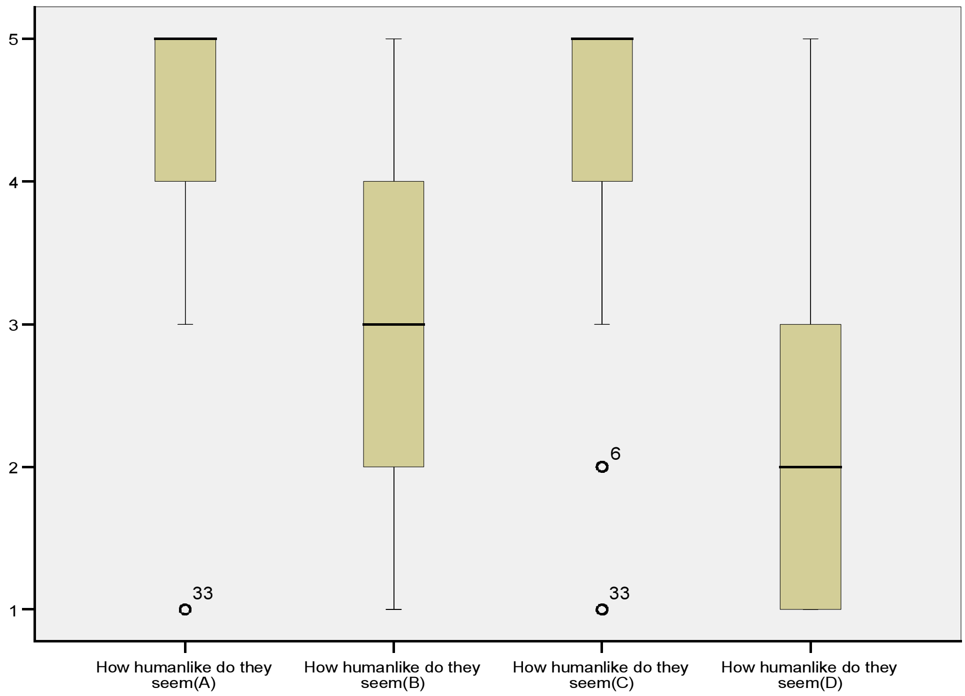


Figure 49: Participants ratings of the robots (A, B, C and D) for human-likeness on a 5 point Likert scale (1 = Human-like, 5 = Not Human-like).

6.4.2 Preferred Robot Type and Comfortable Approach Distance

The four robots used for the LMFE HRI trial runs and those shown as still images to participants for the final questionnaires were all identical apart from the two controlled factors of appearance and height. These two factors were used as grouping factors for GLM (General Linear Model) Repeated Measures Univariate ANOVA tests which examined the effects of participants' preferences on their comfortable approach distances from the live HRI trials with an actual robot over the experimental conditions for autonomy, context and situation. In Section 6.1, it was hypothesized that participants *preferences* for robot appearance and height may also have an effect on comfortable robot approach distances, whichever robot was *actually* approaching. There were 23 short term participants and 12 long term participants. The short-term participant group only experienced a single exposure to the LMFE HRI trial, whereas the long-term group would be going on to participate in a further five weeks of HRI trials. As the different expectations of the two groups might have affected their respective approach distance preferences, Long-term/Short-term was also incorporated as a grouping factor in the analysis. As the results from this study into multiple factors and their effects on HR proximity were still provisional, it was preferable that all possible significant effects on HR proximity were picked up, even at the expense of a small additional probability of gaining false significant effects. Therefore adjustments to the significance thresholds were based on those recommended by Benjamini and Hochberg (BH) which provide a less conservative level of acceptance than Bonferroni correction tests (cf. Benjamini & Hotchberg (1995)) and are shown in the right-most column of Table 11.

Note, that because the effect of a factor does not reach the BH adjusted reliable significance probability level overall ($P < 0.05$), it does not mean that the effect of that factor can be assumed to be null. If the UANOVA predicts that a factor has a significant effect, the balance of probability suggests that this is more likely due to a real effect than by chance. Therefore, although the level of significance probability for a particular factor effect may not be great enough to provide the required degree of confidence, on balance the effect is probably real and may well warrant further investigation in a more focussed experiments .

*Table 11: GLM UANOVA between subjects effects of preferences for robot appearance and height on comfortable robot approach distances. Significant results shown in **bold**.*

Factor	**Mean Square**	**Variance (%)**	**df**	**F**	**Sig. p =**	**Adjusted Sig.** ** **Threshold**
Long-term or Short-term	39603	0.93%	1	1.140	0.311	
Robot Appearance	1487233	34.77%	1	42.813	**< 0.001**	**0.003**
Robot Height	22270	0.52%	1	0.641	0.442	
Preferred Appearance	600611	14.04%	1	17.290	**0.002**	**0.006**
Preferred Height	275311	6.44%	1	7.925	**0.018**	0.013
Long-term * Appearance	42151	0.99%	1	1.213	0.296	
Long-term * Height	13744	0.32%	1	0.396	0.543	
Robot Appearance * Height	5579	0.13%	1	0.161	0.697	
Long-term * Appearance * Height	235414	5.50%	1	6.777	**0.026**	0.016
Long-term * Preferred Appearance ++	0		0			
Long-term *Preferred height	2274	0.05%	1	0.65	0.803	
Preferred Appearance * Preferred Height ++	0		0	0		
Robot Appearance * Preferred Appearance	835251	19.53%	1	24.044	**0.001**	**0.006**
Robot Appearance * Preferred Height	196011	4.58%	1	5.643	**0.039**	0.019
Robot Height * Preferred Appearance	1266	0.03%	1	0.036	0.852	
Robot Height * Preferred Height	173726	4.06%	1	5.001	**0.049**	0.022
Error	347382	8.12%	10			

++ No long-term participants actually interacted with their preferred robot appearance, so combinations for (Long-term * Preferred appearance * X) combinations are empty, and are not shown.
** The significance probability thresholds are adjusted for multiple hypothesis testing (cf. Benjamini & Hotchberg (1995))

It can be seen that, as expected from Syrdal et al. (2007a) the (live trial HRI) interacting robot's appearance has a BH compensated significant effect on participants approach distance preferences. When live robots are encountered, overall participants prefer the humanoid robots to remain at further approach distances (mean = 645mm, SD = 20.43) than the mechanoid robots (mean = 490mm, SD = 20.43). The height of the interacting robot had no significant effect, but the long-term group does exhibit a BH uncompensated significant combined effect due to both the interacting robot's appearance and height on RH approach distances.

There is a BH compensated significant interaction effect between most preferred robot appearance and actual robot appearance. Participants who expressed a preference for humanoid robots, generally tolerated closer approaches by whichever robot they actually interacted with in the live HRI trials. Participants who expressed a preference for short robots, also tended to allow whichever robot they interacted with to approach closer than those participants who preferred a tall robot. In fact, the effect of the *preferred* appearance and height factors accounts for 20.8% of the total variance, nearly two thirds of that for actual robot appearance (34.8%).

These significant results (illustrated in Figures 50 and 48) indicate that participants who *preferred* a robot with a humanoid appearance also tended to allow whichever robot they were interacting with to approach closer (mean approach distance = 555mm) than those who *preferred* a mechanoid robot (mean approach distance = 604mm). Also, those who *preferred* a tall robot, also tended to allow whichever robot type they were interacting with to approach closer (mean approach distance = 516mm) than those who *preferred* a short robot (mean approach distance = 575mm).

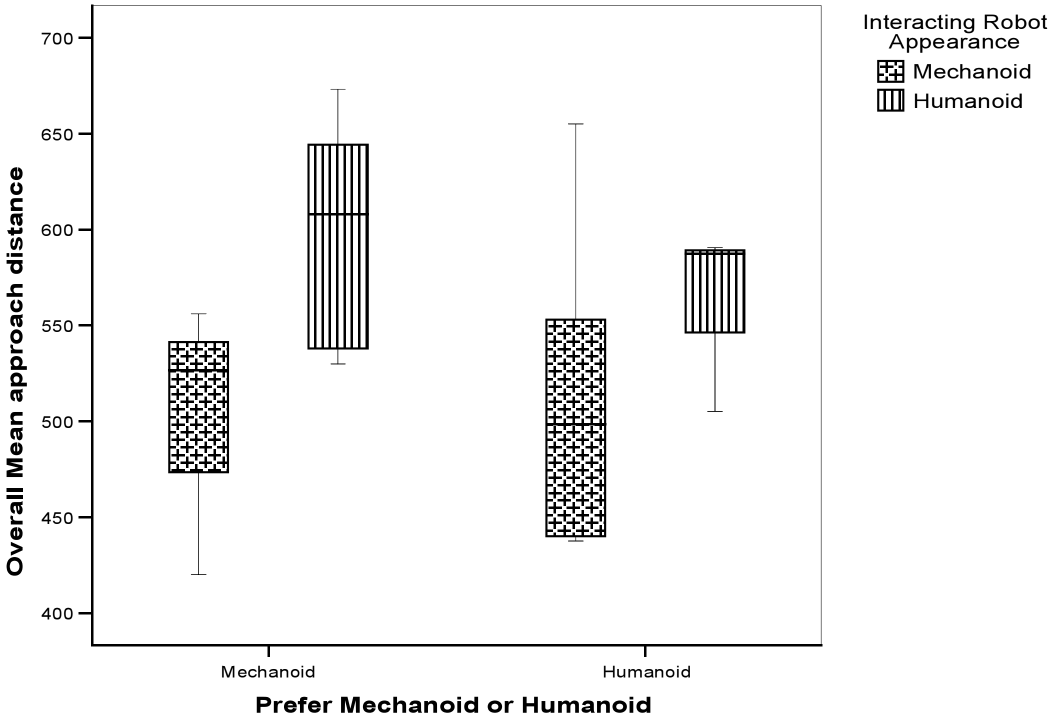


Figure 50: Mean RH Approach Distances vs. Preferences for Robot Appearance.

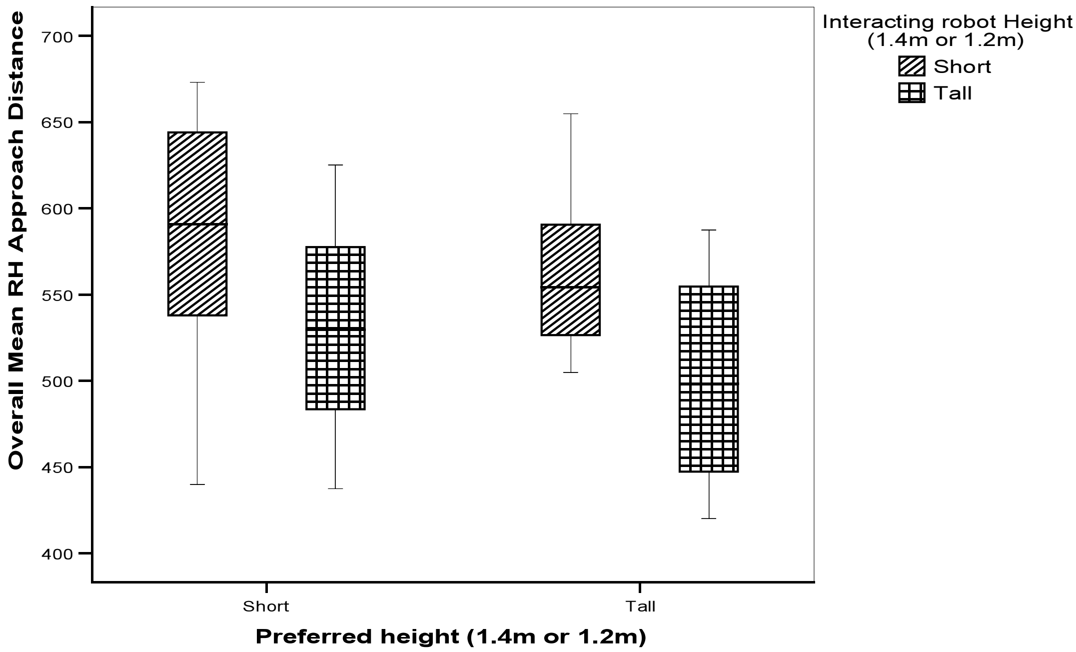


Figure 51: Mean RH Approach Distance vs. Preferred and Actual Robot Height (Short term exposure participants)

6.5 LMFE Discussion and Conclusions

Overall, there was no strong general overall preference for any one of the four robot types. Also there was no strong overall preference for one appearance (humanoid-mechanoid) or height (short or tall). However, there was a significant general tendency that both long term and short term participants tended to prefer either the short mechanoid robot, or the taller, more humanoid appearance robot. It may be that participants fall into two main demographic groups who select their preferred robot for different reasons. The smaller mechanoid robot perhaps because it is perceived as less obtrusive in the home environment, while the humanoid robot is selected because it has more human characteristics and may perhaps be perceived as more entertaining or sociable. There were also indications that the taller robots also were perceived as more human-like, though it seems the influence of robot height is less than that of appearance. Further research would be necessary to investigate why participants prefer their particular choices of robot, but this is outside the scope of the study for this thesis.

We have found that RH comfortable approach distance was affected by the actual appearance, but not significantly by the height of an interacting robot (cf. Koay et al. (2007b)). However I have found that participants expressed *preferences* for both robot appearance and robot height affected their individual comfortable RH approach distances for robot of whatever type. Surprisingly, participants *preferences* for robot appearance and height combined have nearly as great an effect on participants preferred approach distances as the actual interacting robot appearance. There was a difference found for those participants who had expected a longer subsequent period of interaction. The ANOVA shows that there were effects for the long-term group due to the interacting robot's height, but also related to the participants expressed appearance and height *preferences*. It was not possible to test if robot appearance preferences had an effect as no long-term participants interacted with a robot with their preferred appearance. This may be due to a statistical blip, or may be that after five weeks participants did not prefer the appearance of the robot they had been interacting with. More focussed experiments are required to investigate further into the effects on RH proximity for robot appearance preferences and of participants expectations with regard to HRI duration and content.

These are interesting findings and if likely default or pre-set comfortable approach distances for HRIs are known for a range of possible domestic robot appearances and heights, it would allow robots with particular appearances and heights to exhibit acceptable default proxemic behaviour. Therefore, a robot that had been bought or selected by an individual or members of a household for domestic or private use, could potentially have pre-set default parameters for governing proxemic behaviour. These pre-set comfortable approach distances would be suitable for a range of contexts and situations, and the exact default values would depend on the particular combination of robot appearance (on a mechanoid to humanoid scale) and the height of the robot.

The distance between robots and humans can be readily measured by current robot sensors. Also, human social spatial distances define, initiate and moderate many social aspects of human non-verbal behaviour. It is hoped therefore that in future a robot could use robot-human measured distances, both as a measure of human state, perception and intent, but also as a parameter which can be manipulated or adapted in a general or individual basis in order to increase the effectiveness and social acceptability of HRIs by domestic robots. In order to develop a reliable method for using robot appearances and heights in this way, more HRI based studies would be required to establish suitable proxemic distances for use in a wider variety of contexts and situations, and with a range of possible robot appearances and heights.

6.6 Chapter Summary

This latest HRI trial was carried out to test the hypothesis that many factors may affect participants preferences specifically with regard to robot to human approach distances. The factors investigated here included those which were manipulated for a set of HRI trials which controlled conditions for robot appearance, task context and situation, notions of robot autonomy and control, and humans' preferences and perceptions for robot appearance and behaviour. To facilitate such a complex HRI trial, the experimental methodology and set-up was enhanced over previous trials by allowing direct annotation on the video recordings of the trials of when participants thought the robot was close enough. These preferred approach distances were also logged automatically by the robot sonar and laser range systems.

There was was not a clear single optimal combination of robot appearance and height with regard to robot type most preferred by participants. There was a significant general tendency for participants to prefer either the tall humanoid robot or the short mechanoid robot. It was suggested that this may be due to participants internal or demographic factors, leading them to prefer different main attribute set for a domestic robot. Tallness as a robot attribute seems to reinforce their perception as being more human-like.

I also found that Participants *preferences* for robot height and appearance were both found to have significant effects with their preferences for live RH comfortable approach distance, irrespective of the robot type they actually encountered. The effect on comfortable approach distance preference for *preferred height* was significant, even though *actual robot height* did not have an effect on comfortable RH approach distances. With further HRI studies to provide more quantifiable results, potentially this could be used to predict users likely preference or tolerance for RH approaches, and other aspects of robot proxemic behaviour over a greater range of contexts and situations

6.6.1 Responsibility for Work Performed

The study was jointly devised, set up and carried out by myself and my colleagues, Kheng Lee Koay and Dag Sverre Syrdal. The analysis and discussion of the comfortable approach distance data combined with participants preferences for robot types presented here was performed by myself and these findings have been submitted for publication (cf. Walters et al. (2008)).

I made all the major mechanical and systems changes to one of the PeopleBot™ robots in order to produce a shortened version to be used for the tall and short robot height conditions in the LMFE Trials. I also developed much of the HRI trial systems relating to data collection and automatic annotation of the HRI trials video recordings.

Chapter 7: A Framework for HR Proxemic Behaviour

In Chapter 3, a series of exploratory experiments investigating Human-Robot proxemics was presented. The main conclusion from these experiments was that humans perceive and respect the interpersonal social space of robots. The results obtained also confirm previous findings that people respect the interpersonal distances for both animated agents in IVEs and robots (cf. Bailenson et al. (2003), Breazeal (2004) & Nomura et al. (2007)). The study in Chapter 6, which investigated peoples perceptions, preferences and ratings of the experience of interacting with a domestic service robot in a realistic HRI scenario has provided a number of further insights into how people judge, perceive and rate domestic robots. Based on these findings, I here propose a framework for the study of human-robot proxemic behaviour, which can be used to predict and interpret aspects of HR interpersonal distances based on these findings.

Table 12 shows the factors for robot appearance and preferences, interaction context and situation which have been found experimentally to affect the distances that humans take towards mechanoid and humanoid robots (cf. Chapter 3, Walters et al. (2005a), Walters et al. (2006), & Walters et al. (2008); Chapter 6, Walters et al. (2008a), Syrdal et al. (2007) & Koay et al. (2007b)). The table provides estimates of default settings, which would be suitable for most humans in the given situations and contexts. Some values are predicted estimates based on previous experimental results (see Chapter 3) which indicated a relatively high degree of symmetry between similar HR and RH approach distances, but were not directly observed in the controlled conditions of the HRI experiments performed for the study (see Chapter 6). The default settings are given as relative adjustments or corrections to the overall default approach distance of 57cm. This figure was the calculated grand mean preferred approach distance for the large scale trials in Chapter 6. It was taken over all 33 participants preferred approach distances, measured over all the trial conditions for robot autonomy, interaction context, situation and approach direction. It is also close to the mean approach distances obtained by Stratton et al. (1973) for both humans (20in = 51cm) and a tailors dummy (22in =56cm) used as a control, in their proxemic experiments investigating "comfortable" approach distances for low and high "self concept" (i.e. status) humans approaching each other.

Table 12: Factors which affect HR interpersonal distances

Factor	Situation(s)	Context(s)	Base Distance = 57cm Estimated Adjustment for Factor (cm)
Attribute or Factor of Robot			
Mechanoid Robot	RH Approach HR Approach	All	-3 -7
Humanoid Robot	RH Approach HR Approach	All	+3 -1? (Estimate, not confirmed)
Verbal Communication	RH Approach	Verbal Interaction	+3
Giving object	RH Approach	Physical Interaction	-7
Taking object	RH Approach	Physical Interaction	-7? (Estimate, not confirmed)
Passing	RH Approach	No Interaction	+4
Direction from:	RH Approach	Front Right/Left	+2 -2
Attribute or Factor of Human			
Preferred robot Humanoid	RH Approach	All Private	-3
Preferred robot Mechanoid	RH Approach	All	+3
Preferred Height Tall	RH Approach	All	-1
Preferred Height Short	RH Approach	All	+2
Uncertainty or perceived Inconsistency	HR Approach	Initial Encounter	+15
Verbal Communication	HR Approach	Verbal Interaction	+3
Giving object	HR Approach	Physical Interaction	-7? (Estimate, not confirmed)
Taking object	HR Approach	Physical Interaction	-7? (Estimate, not confirmed)
Passing	HR Approach	No Interaction	+4

Using the relative differences given in Table 12, a default approach distance estimate can be calculated for a robot encountering any combination of proxemic factors in the first column.

For example, consider the case where a Humanoid robot is approaching a human to hand over an object. Look down the left hand column and note all the factors which apply, then calculate the default approach distance for the particular situation and context. In this case, the distance would be: (Base distance =) 57cm + (Humanoid-RH Approach =) 3cm - (Giving Object RH Approach=) 7cm = 53cm. If other factors are known (e.g. if the preferred height was short, then adjust by -1cm), then they can also be incorporated into the calculation. As other factors which affect HR proximity become known or quantified, they can be incorporated into the framework and used to refine or extend the applicability of the proxemic estimates produced.

If a particular factor is not known, then it is wise to err on the side of caution and assume that the furthest distance would apply. An approach that was was too close might be interpreted as invading the human's personal space, while an approach that was slightly too far away would be perceived as keeping a respectful distance. For example, if the human's preference for height is not known, it is safest for the robot to assume that their preference is for small robots as this would ensure that any error in approach distance positioning by the robot would result in an approach distance that would be further away than might actually be preferred. It should also be possible to incorporate (modified) rules, with appropriate weightings for Hall's social and public spatial zone distances to provide for appropriate proxemic behaviour by the robot over larger distances in open areas (cf. Koay et al. (2006)) and for different physical situations. This approach also lends itself to incorporating other different scales for the rating of robot appearance. It should allow the experimental assessment and estimation of factor values for robot appearance scales along both the realistic-iconic, realistic-abstract or machine-organic dimensions (cf. Chapter 2, McCloud (1993) & Dautenhahn (2002)).

This method assumes that the factors are linear and independent. However, the number of robot types studied here is too few to make any conclusions as to the form (linear or otherwise) of the relationships between the factors examined (e.g. robot appearance) and the numerical value of their effects. There are also indications that some of the factors are dependent on each other. For example, from Chapter 6, Table 11, it can be seen that the factors for preferred robot appearance and actual robot appearance have a combined effect on participants' preferred robot approach distances. In this case a practical approach would be to apply a further adjustment by a correction factor if both factors are present. The appropriate scale factors could be incorporated into the framework, either by a summative superposition of the factors, or possibly there would need to be various correction factors to compensate for inter-factor effects. Probably the most effective approach to implementing these corrections in a practical system would be by means of a look up table. It should be noted that when implementing automatic control systems for many real world systems, few actually exhibit linear behaviour. However, a useful simplification can often be achieved by assuming a linear response. This will often provide a reasonably precise control output without having to implement more sophisticated non-linear control methods.

In order to test, verify and extend the assumptions and application of the HR Proxemic Framework, the next stage would be to conduct live HRI proxemic experiments with this HR proxemic framework implemented in the form of a prototype HR proxemic system on a range of robots with different appearance and behavioural attributes. Fine adjustments of human-robot interpersonal distances according to a number of observed factors (as proposed by Walters et al. (2005b)) related to internal qualities of the interacting humans, intrinsic robot attributes, and the external physical situation and task context, is a promising direction towards a true robot companion that needs to be individualized, personalized and will adapt itself to the user as suggested by Dautenhahn (2007).

7.1 Implementation of a HR Proxemic System

A HR proxemic system based on this HR Proxemic framework could probably be implemented using an Artificial Neural Network (ANN) which could learn and correct for the various values for the factors and inter-factor effects. I propose that a prototype implementation using a fuzzy logic based control system would be particularly well suited for verification and further research purposes. It would allow the incorporation of the various HR proxemic factors by means of fuzzy rule sets. The various weightings of the factors can then be dynamically "tuned" by means of a number of well known learning algorithms (cf. Zadeh (1968) & Cox (1994)), perhaps using the CLD (cf. Chapters 4 and 6) to obtain user's feedback in real time. This would provide a learning mechanism so the robot could effectively adapt its proxemic behaviour over time in order to best satisfy individual users preferences and requirements. The advantage of a fuzzy logic based control system is that it is possible to examine the values of the weighting and parameters for the fuzzy rules. As the robot becomes acclimatised to the proxemic preferences of more users, contexts and situations, it should be possible to interrogate the fuzzy system proxemic factor weightings, and thus work back to estimate and explore the relationships between HR proximity and the various influencing factors.

7.2 Summary

A first empirical framework of Human-Robot proximity is presented which shows how the robots own measurement of HR interpersonal distance can then be used by the robot to predict and interpret (in terms of the robots own limited view of situation and context) the proxemic control requirements and the active likely factors for a particular HRI. The framework provides for incorporation of inter-factor effects, and can be extended to incorporate new factors, or updated values and results.

To verify the HR Proxemic framework, and to extend the applicability to a wider range of contexts and situations, a prototype HR proxemic system based on the framework should be implemented on a range of robot platforms in order to run experimental HRI trials.

Chapter 8: Overall Discussion

Two complimentary aspects to this study fall broadly into two categories: HRI experimental methodology development, and scientific findings. Scientific findings from the exploratory studies (cf. Chapter 3) have indicated the areas for further investigation, and this has directed the necessity for the developments in HRI methodology (cf. Chapter 4) in order to progress these investigations (cf. Chapters 5 and 6). These aspects are considered in the following sections:

8.1 HRI Experimental Methodology Development

The data for this study was gained from the combined results from experiments performed as part of seven separate series of HRI trials (cf Chapter 1, Table 2). The trials provided results for HR proximity under controlled conditions including different robot appearances, height, behaviors, interaction context and situations. The findings related these factors to the human participants perceptions and preferences for various aspects of robot appearance and behaviour. The discussion of the HRI methodological issues here focusses on aspects of the HRI trial methodology which are directly relevant to the experiments presented for thus study.

8.1.1 Exploratory Proxemic HRI Trials: Methodology Issues

In practical terms, if the method of making distance measurements is described for any HR proxemic study, then it is possible to compensate for the different datums and measuring methods used. However, it would be desirable for all practitioners in the field of HRI to adopt a standard measure of proximity between humans and robots at this stage, while there are relatively few researchers in the field, in order to avoid many of the measurement problems which have arisen in the field of human proxemics. This is especially pertinent for HR proxemics in particular, because robots will always provide relatively accurate quantitative measurements of distances. It would be a benefit for robotics designers and practitioners to use directly the proxemic results from HRI experiments and the data points for measuring HR distance to be defined for both wheeled, tracked and legged robots, and for approaches from all direction and orientations. It is proposed here that a working standard means of measuring HR distance could be defined as follows:

The distance between a human and a robot to be that measured between the nearest opposing static body parts of an interacting human and robot, but not including any arms or manipulators reaching out.

It is straightforward to compensate the values obtained from the robots internal range sensors to obtain a standard value which is directly comparable (cf. Chapter 6). In principle, this definition of HR proximity should also be able to take account of situations where the human or robot are leaning away from, or towards, each other.

The real world setting of the third set of HR approach experiments posed problems with regard to control of experimental conditions in the environment (cf. Chapter 3). However, in many ways the results gained from these trials were the most rewarding. In Chapter 3 it was concluded that the extraneous factors such as the audience and the social nature of the setting did not affect or influence the results gained from the experiment adversely. An earlier comparable experiment in a simulated living room under controlled conditions, provided similar results for the portion of results where they could be directly compared. A desirable aim therefore for all future HRI trials, is to use as naturalistic a setting as possible (cf. Sabanovic et al. (2006)).

8.1.2 VHRI Trial Development and Methodology Issues

The next set of HRI trials investigated physical aspects of robot non-verbal behaviour, using a scenario based on fetching and carrying objects to humans participants in various situations and contexts. My prime role during this period was in the development and verification of the novel video based HRI methodology and other HRI trial methods and procedures (cf. Woods et al. (2006a) & Walters et al. (2007)), which were necessary for the investigations for the next stage of this study. The original idea of using Video for HRI trials was mine, and I was instrumental in developing much of the video shooting and editing techniques to meet the objectives for creating the VHRI trial videos (cf. Chapters 4 and 5).

Issues of people's perceptions of consistency of robot appearance and behaviours were investigated in Chapter 5. I developed an original analytical method which was able to assess the degree of consistency of various components and features of robot appearance and non-verbal behaviour. This was applied to the analyses of results from an exploratory HRI trial investigating issues of how people perceive and rate consistency in robot appearance and behaviour. This trial used the new VHRI methodology which was developed to prototype, explore and pilot ideas, concepts and fertile areas for investigation before investigation and verification in more resource intensive live HRI trials (cf. Walters et al. (2007d) & Walters et al. (2008a)).

8.1.3 Main Multiple Condition HRI Trials: Methodology Issues

The LMFE HRI trials (cf. Chapter 6) were the most complex set of live HRI trials we had run to date as a group. The number of main controlled experimental conditions in the trials included robot autonomy, HR interaction context and situation, and robot appearance and height, forming a main condition matrix of 2 x 3 x 2. On top of these main conditions was effectively superimposed another (2 x 2) condition matrix for robot appearance and height which provided some of the data relevant to this thesis. Due to the large number of experimental conditions, the statistical analysis of the experimental comfortable approach distance data obtained from these HRI trials therefore runs the risk of gaining false significant results. A correction for multiple condition (cf. Benjamini & Hotchberg (1995)) which controls the FSR was applied to the significance level in order to make sure that probable significant effects were uncovered. It is important to note that findings of effects which did not meet the Benjamini & Hotchberg significance criteria, are not then discounted as not having an effect. It is still on balance likely that these are real significant effects, just that there is a relatively higher probability ($p > 0.05$) that they may be due to chance. It would not be wise to put too much confidence in these results and therefore it is desirable to carry out further more focussed HRI experiments to assess the true underlying significance of these effects. This issue is discussed with regard to particular results in section 8.2.

The effort and expense involved in the planning, preparation and running of this particular series of LMFE HRI trials was relatively large, but the experimental results and data obtained were relevant not just to this thesis, but also to other studies and aspects relevant to my colleagues and other members of the COGNIRON academic team. These LMFE trials were repeated over five weeks to assess how people's perceptions changed during this period of exposure (cf Koay et al. (2007b)). Other experiments which ran during the live trials period included those which had used incidental data collected on participants personalities for the main longitudinal trials (cf. Syrdal et al. (2007)) and a number of short, qualitative type scenario based exploratory investigations whose ostensible purpose was to expose participants to the robot during the five weeks, but also allowed the opportunity to explore more speculative aspects of HRIs. The experiments detailed in Chapter 6 relevant to this thesis utilised approach distance data from the main trials series, from interactions with live robots, in combination with both participants preferences for robot appearance and height. Planning and preparation for these HRI trials was an iterative process, with (often) hard bargaining carried out to arrive at a coherent set of incorporated experiments which satisfied the interests of all the researchers involved! Provisional HRI trial plans also had to be approved by the UH Ethics Committee as they involve the use of human participants. Setting up and carrying out the HRI trial series requires expertise in technical, scientific and organisational areas including: technical robotics and engineering, management and logistics, HRI and HCI, psychology and analysis.

It is impossible to run a large HRI trial, of the types presented in this thesis, without the input and support from a dedicated team. Over the five weeks of the LMFE HRI trial, we ran over 120 separate HRI sessions. Each session took around an hour to complete and the work involved in just keeping the two robots and the experimental and data collection systems running reliably for such a continuous period was challenging. In such a long period of trial participation, it should be expected that the robot and trial hardware will break down at some points. It is good practice to have the second robot ready to go in case the first one has a problem (cf. Chapter 2.4). It is also useful to have alternative participants available flexibly at short notice in order to fill in spare session slots where participants fail to keep appointments. Also, all the HRI trial data collection systems should have alternative backup systems running, or available to be used to replace faulty components. For example, we use at least two video camera systems to record each HRI trial, two CLD receiver systems for logging/recording RH comfortable approach distances, and all the trial operators separately keep their own records of participant, experimental conditions and reconcile them after each trial run.

8.2 HRI Scientific Findings: Discussion

A main finding from the experiments presented in previous chapters was that humans perceive and respect the interpersonal social space of robots. The results obtained have also indicated that the majority of proxemic distance measurements for humans approaching a robot, and for a robot approaching a human fell approximately within the broad framework of Hall's interpersonal spatial zones theory. This confirms previous finding from HCI and for zoomorphic robots (cf Bailenson et al. (2003) & Breazeal (2004)) that people respect the interpersonal distances for both animated agents in IVEs and robots.

These studies have also provided evidence that there are a number of different factors which can affect the interpersonal distances people take towards robots. In particular, findings from the three initial exploratory HR proxemic trials (cf. Chapter 3) suggest that voice style, which is a non-verbal characteristic of robot behaviour, affects humans' initial comfortable approach distances to a mechanoid robot. Participants tended to keep further distances from robots which seem to have been perceived as initially exhibiting inconsistent appearance and (voice style) behaviour and therefore perhaps perceived as slightly disconcerting. This effect was relatively short lived as it seems that participants who had experienced only a few minutes previous exposure to the robots did not exhibit an increased approach distance. It was observed in a group of participants who mostly had previous experience with using and working with robots, and also under natural (non-laboratory) real world conditions. It can be argued that the participants were not representative of the general population and may possibly be particularly receptive to treating robots in an uncertain way due to their background in robotics. However, other HR approach distance findings from this trial were similar to those obtained under comparable conditions from the previous initial proxemic experimental trials which used robot naive participants. This is an indication that previous experience with robots in general, may not in fact affect an individuals response to an initial encounter with a particular robot. The number of robot voice types in this study was limited to three. Therefore it would be desirable for future experiments to extend the range of robot voices investigated.

The HRI experimental findings presented for this thesis are the first that have investigated interpersonal spaces between robots and humans at a deeper level than simply assuming or relating them to Hall's social zone distances. Our experimental findings have also shown that people's preferences for robot approach distance are affected by both the context of the interaction and the situation (cf. Chapter 6, Koay et al. (2007b)). People will tolerate closer approaches for physical interactions, as opposed to verbal and no direct interaction conditions. These findings relate to the situation where a robot approaches a human. However, it would be desirable to perform similar experiments to see if the same preferences for approach distances were obtained for situations where humans approach robots. In previous experiments for this study (cf. Chapter 3), I found that the HR approach distances people took when *approaching a robot* were highly correlated with their RH approach preferences for when the *robot approached* them. There were some indications that participants preferences for RH comfortable distances were also slightly greater than their observed HR comfortable approach distances. This may indicate that the robot was perceived as relatively lower status compared to the participants (cf. Gillespie & Leffler (1983)). However, this finding is tentative and needs to be verified and experimentally tested under a range of conditions for contexts, situations and robot types.

The scientific findings with regard to the PS and MS VHRI trials studies investigated participants preferences for robot approach direction and have mainly been reported in conjunction with other members of the team (cf. , Dautenhahn et al. (2006), Woods et al. (2006), Koay et al. (2007a) & Syrdal et al. (2006)). These are summarised in Chapter 4. The main parts relevant to this thesis are focussed on the development of the novel VHRI methodology and have been covered in the previous chapter section 8.1.

All the robots used in these experimental studies studies had appearances that tended towards the machine-like end of the machine-human-like appearance scale (cf. Chapter 2). For the first five sets of HRI trials documented in Chapters 3 and 4, the robots used had a mechanoid appearance with no explicitly human-like features at all, apart from a simple 1 DoF lifting arm. For the last two studies presented here, which included robot appearances as one of the controlled variables, the most humanoid robot had only two attributes which were anthropomorphic; a simple metallic head and two aluminium framed, mechanical-looking, 7 DoF arms (similar to human arms in configuration), with simplified "hands". A finding from both the RABE VHRI study (cf. Chapter 5) and the LMFE HRI trials (cf. Chapter 6), was that most participants preferred the robot appearance which they rated as more human-like. As anticipated, this confirms that the humanoid robot used for this study was not human-like enough to trigger the "uncanny valley" effect noted by Mori (1970). This also supports the view that a degree of human-like appearance and behaviour can facilitate HRIs (cf. Minato et al. (2004a) & Goetz et al. (2003)). Probably a more explicitly humanoid appearance than that used for the investigations for this thesis is required in order to achieve an optimum level of human-likeness which will suit most people's preference for robot appearance.

It is necessary to perform more HRI experiments in order to confirm and find the exact magnitude and form of these interaction effects over a wider and more finely graduated range of machine-like to human-like robot appearances for a number of various behaviours, situations and contexts. There were also substantial minorities who preferred the small mechanoid robot. Syrdal et al. (2006) in a separate experiment carried out in the same RABE VHRI trial series examined participants personality traits and found that participants with more introverted personalities tended to prefer mechanoid robots. It is likely that people's preferences and perceptions of other attributes of robots are affected by their personality characteristics. The investigation of participants personality, and interaction effects with their perception of robot personality is outside the scope of this thesis, but enough evidence has been gained from the findings presented here to support the desirability of further research in this area.

From the RABE VHRI trial (Chapter 5), a main finding was that people's ratings of robots from static appearance from pictures on the machine-human-like scale are strongly indicative of their overall likely *initial* perceptions of a particular robot when they experience both the robot's appearance and behaviours. This confirms findings by others that humans make their initial judgements of robots (as is the case for other humans) primarily on their initial appearances (cf. Lee & Keisler (2005)). In the PRVE HRI trial (cf. Chapter 3) where robot-experienced participants encountered mechanoid robots with different voice styles, evidence was found to indicate that people can modify their initial impressions and perceptions of a robot relatively quickly after experiencing an actual encounter or interaction.

It should also be noted that some participants in the final LMFE study (Chapter 6) rated the tall mechanoid robot as human-like. This result warrants further investigation as it seems that these participants may well have judged the degree of human-likeness of the robot on factors other than their initial perceptions of appearance after a relatively short exposure to a live robot. Their questionnaire responses were gained after their HRI trial interaction, so possibly once they had interacted with the robot in the final live HRI trial scenario, they may have perceived other non-verbal factors as more important indicators of human-likeness than robot appearance. This also confirms the finding from the HR proximity HRI experiments (cf. Chapter 3) that people seem to modify and refine their initial perception of a robot after a relatively short time, possibly of the order of a few minutes.

The final study (Chapter 6) which investigated people's perceptions, preferences and ratings of factors relating to the experience of interacting with a domestic service robot in a realistic HRI scenario has provided a number of insights into the factors that people use to judge, perceive and rate domestic robots. All the robots used in the study were classed as mechanoid or humanoid, but not enough to exhibit an "uncanny valley" repulsive effect (cf. Mori (1970) & MacDorman (2006) & Lohse et al. (2007)) which people found disconcerting. The present thesis experiments investigated robots with appearances rated towards the mechanical end of the machine-human-like scale. However, there are a number of other scales that have been proposed for rating robot appearances such as realistic-abstract or realistic-iconic (cf. Dautenhahn (2002)), or biological-artificial (cf. Chapter 2). It is desirable for future HRI experimental trials to investigate the use of other appearance ratings scales in order to explore more fully the possible design spaces of robot appearances and consistent behaviours.

A number factors investigated in the LMFE trials were found to have effects on RH comfortable approach distances. A correction was applied to the "raw" significance values obtained in order to compensate for the large number of factors considered in these experiments (cf. Chapter 6 & section 8.1). The factors which were found to have adjusted significant effects over all the conditions ($P < 0.05$) were the appearance of the interacting robot, the appearance preferences of the participants and also between robot appearance and appearance preferences. Some factors exhibited effects which did not meet the level of adjusted statistical significance required. However, it is not safe to discount these results as not relevant, as (I argue in section 8.1) there is a balance of probability that these are real effects. These probable factors include participants' preferences for robot height, between robot height and preferred height, and also between expectations for HRI contact duration, preferred robot appearance and robot height. Therefore it is desirable for future HRI experiments to both verify the effect of the adjusted significant factor effects, but also to assess the true state of the probable factor effects.

Participants' preferences for the factors of robot appearance and robot height were explored. A possible finding is that the participants fall into two main groups: A majority group who preferred the tall humanoid robot (D), and a minority who chose the small mechanoid robot (A). It may be that the first group may have chosen their preferred robot type because they perceive it as having more human-like social qualities. Whereas the latter group perhaps preferred a robot which they believed would be unobtrusive, both physically and in terms of requiring social attention from the user. Syrdal et al. (2007a) has found that people who exhibited more introverted personalities also preferred a more mechanoid robot appearance, and also preferred robots to keep larger interpersonal distances. It would be desirable therefore to perform more focussed HRI studies in order to investigate this aspect in a controlled experiment. If a significant effect can be found that indicates that people who were more introverted also preferred robots that were not just mechanoid in appearance, but also robots with behaviour which is more unobtrusive overall, this would be an important finding. In practical terms it would mean that people who chose a small mechanoid robot for their own domestic services, could also have many of the default values for social and spatial behaviour set accordingly to take account of the likely preferences commonly associated with the introverted personality of the new human owner or main user. It is likely that different robot appearances and attributes may be more acceptable to different users. For example, a discreet servant or even a silent servant, with no obvious initiative or autonomy (cf Dautenhahn et al. (2005)).

The findings presented in this thesis have been gained from relatively large scale experimental HRI Trials, typically with several tens of participants. However, compared to similar demographic studies and statistical analyses from comparable psychological and clinical field trials, the participants sample sizes are small and their duration of exposure to the interacting robots limited. This is not a fault of the experimental methods or the researchers involved, but reflects the difficulty, resource intensive and time consuming nature of running controlled HRI trials with WoZ or current robot technology. In order to perform more exhaustive studies, it is necessary to develop more autonomous robot capabilities to allow the HRIs to be carried on for longer periods. Also, the continuing development of data collection and analysis systems which can allow the continuous monitoring of HRI experiments over extended periods (cf Chapter 2.4). This will also allow the deployment of robots and the running of experiments in real world situations. The robot house used in the later HRI trials documented here is the best we can achieve at present at achieving an ecologically valid trial environment. Only when HRI trials can be performed in participants *own* homes will it be possible to achieve a realistic HRI trial environment.

As a contribution to achieving this aim, the HR proxemic findings have been collected together and presented in the form of relative differences from the overall defaults approach distance of 57cm (measured from the shortest distance between interactants body parts, cf. Chapter 2.4 & Chapter 7, Table 12). The relative distances have been used to develop a predictive and interpretive framework for HR proxemic behaviour, which is proposed as a first stage for further investigations towards a more complete theory of HR proxemics. By utilising the framework to implement a working prototype HR proxemic control system on a range of robot platforms, the design space of robot appearance, attributes and HR proxemic behaviour can be explored systematically. Almost certainly, the prototype HR proxemic system will exhibit shortcomings and many of these have already been identified (cf Chapter 7) with regard to novel contexts and situations. More critically, the functional forms of the relationships between robot appearance, context, situation and proxemic behaviour have been assumed to be linear in the current HR proxemic framework, but it is likely that this will not be the case. It may be that the framework and associated proxemic theory can be modified and extended in the light of future experimental findings, or it may be that the framework will have to be replaced eventually with another that reflects the HR proxemic functional relationships more directly. In either case, implementation of the framework in a working robot proxemic control system is a pre-requisite to performing the further necessary HRI trials.

8.3 Summary

HRI trial methodology issues and developments relevant to the study have been discussed and reviewed. Findings from the HRI experiments performed for the study have been discussed as a coherent body of evidence and a number of open questions have been identified. The findings from this study support the conclusion that people automatically treat robots socially (cf. Reeves & Nass (1996)). There is evidence to show that they have preferences for interpersonal distances between themselves and robots according to various internal and external factors, and therefore have expectations that robots should exhibit appropriate social spatial behaviour. The experiments performed for the study have mainly been exploratory in nature, and the number of factors under consideration has been necessarily limited. There is a need for long term trials with a variety of types of robots in order to determine which social features are most effective at making human robot interaction robot more efficient and useful to humans. Implementation of the HR proxemic framework in the proxemic control system of a range of robot types is seen as an important tool for future HRI research aimed at developing a more complete theory of HR proxemics.

Chapter 9: Conclusions, Contribution to Knowledge and Future Work

Investigation of the original hypothesis, (cf. Chapter 1) has inspired, guided and set a clear boundary to the research and work undertaken for this thesis:

> *Hypothesis: Attributes of robot appearance, behaviour, task context and situation will affect the distances that people will find comfortable between themselves and a robot.*

The issue of HR interpersonal distances and social proximity was driven by the fundamental nature of proxemic sensing systems and measurements to robot navigation and the ready availability of distance measurement systems which can now reliably recognise and obtain distances to humans within robots' task areas. This thesis has found evidence supporting the hypothesis. This evidence and other outcomes from the thesis are reviewed and summarised below:

9.1 Conclusions and Review

Chapter 3 presents three exploratory trials which investigated comfortable HR and RH approach distances which concluded:

- Humans respect interpersonal distances for mechanoid robots, and this reflects their perception of a robot as a social entity. However, experimental findings have indicated that people do not relate to a robot in many of the ways that they would relate to another human (cf. Reeves & Nass (1996), Breazeal (2003), Walters et al. (2005a) & Walters et al. (2006)).

- HR interpersonal distances are shown to exhibit some of the richness that is found in human-human interpersonal distances (cf. Horowitz et al. (1964), Sommer (1969) & Stratton et al. (1973)). There are also specific individual differences in peoples' proxemic responses to robots. Some of the factors affecting HR proximity have been investigated experimentally and have been provisionally quantified (cf. Chapter 3, Chapter 7 & Walters et al. (2008)).

- There were indications that people changed their initial perceptions after only a few minutes of exposure to a particular robot.

The initial HR proximity experiments only examined humans' reactions over periods of exposure to robots of a few minutes to less than an hour and the findings can only be applied to the mechanoid PeopleBot™ used in the initial HR proximity experiments. Conceivably, the findings might be extended to include similar mechanoid robots. It is probable that robots with different appearances will be perceived and treated differently. The PRVE HRI trial found that there were HR proxemic effects related to the robot voice style used. Only three different voices were used, two of which were recorded human male and female voices. The effects of robot voice style combined with non-mechanoid robot appearances was not considered in this study.

A novel VHRI methodology methodology was employed to carry out the RABE trial which investigated human perceptions of robot appearance, behaviour, attributes and capabilities (cf Chapter 5). The conclusions drawn from the RABE study were:

- The VHRI RABE trial produced evidence that users perceive a high degree of correspondence between static appearance and dynamic robot appearance and behaviour. This supports findings by others that initial robot appearance is important in forming users' perceptions of robots (cf. Lee & Keisler (2005)).

The VHRI methodology has been shown to provide comparable results to live HRI trials under a number of well defined situations and contexts. In general, where the interaction involves a greater degree of contingency, the method becomes less viable. It does have the ability to reach large numbers of participants in a short period of time. However, it is not a replacement for live HRI trials and VHRI findings should be verified by live HRI trials. The LMFE HRI trials, presented in Chapter 6, confirm the findings from the RABE VHRI trials with regard to robot appearances, but the findings with regard to gesture and light signals have yet to be verified in live HRI trials.

Chapter 6 presents findings from LMFE HRI Trials which investigated participant's preferences for robot appearance and height, task context and situation, and quantified their effects on approach distance. The conclusions drawn from the LMFE trial findings are:

- The effect of a number of factors on HR personal approach distance preferences have been provisionally quantified. The findings indicate that peoples *preferences* for both robot appearance and height probably have an effect on their comfortable approach distance preferences for any robot type. There is evidence of a link between a preference for mechanoid robot appearance and introverted personality. Further investigation in this area is desirable, but outside the scope of this thesis.

These LMFE HRI trials (cf. Chapter 6) found differences in HR proxemic preferences for two different robot appearances only. The findings indicate that it is probable that HR approach distance preferences will tend to be further for more human-like robots, and closer for more machine-like robots. However, the form of the functional relationship (if there is one) between robot appearance and proximity can only be established by more finer gradated proxemic HRI experiments investigating a range of robot appearances ranging from machine-like to human-like. There are other robot appearance rating scales (realistic-iconic-abstract, zoomorphic etc.) which may provide a more suitable measure for assessing HR proxemic behaviour in conjunction with other forms of robot appearances and behaviours.

A framework for HR proximity is proposed to account for observed values for proxemic distances obtained experimentally in the HRI trials presented in this study (cf Chapter 7). Effectively these are initial parameters and default settings for a robot proxemic system which would allow the robot to exhibit socially acceptable interpersonal spatial behaviour. A mechanism for implementation, testing and extension of this framework is proposed. A HR proxemic framework might be used in two ways:

Interpretive - as an interpretive tool for calculating effects of known factor values, and using the values of residuals to interpret the (robot's limited) context of a situation. If both the context and situation are known, then it may be possible to assess the internal state of the human or to predict the likely effect(s) of movements within a human user's interpersonal social space.

Control - To control a robot movements within the interpersonal space of a human user or partner, so that the robot can exhibit appropriate spatial behaviour which avoids annoying or unsettling the human users, and to facilitate interaction.

As stated, the proposed HR proxemic frame work assumes a linear relationship between robot appearance, contextual and situational factors, and HR proxemic preferences. Almost certainly, this assumption will be found to apply at best over a limited range of robot appearances and behaviours. The framework is flexible enough to be extended and incorporate a number of special case rules and exceptions, and is suitable to be used to develop and implement a prototype HR proxemic robot control system. It is likely that it may prove to be too limited in the long run, but the ability of the HR Proxemic framework to provide consistent automatic robot proxemic behaviour will enable a systematic investigation of HR proxemic preferences to be undertaken.

With the exception of the LMFE HRI trials (cf Chapter 6) the experiments presented in Chapter 3 to 5 were highly exploratory in nature. The prime purpose of running exploratory trials is to be innovative and for this study was worthwhile in that the findings have provided significant evidence that HR interpersonal distances are affected by a number of factors including robot appearance and non-verbal attributes, task context, situation and intention. With hindsight, based on the experiences and findings gained from the series of exploratory HRI experiments investigating HR proxemics, there are a number of further research questions that have become apparent and have been used to design the next series of methodology innovations and HRI experiments. Later experiments build upon the findings and experiences gained from earlier HRI experiments and trials.

9.2 Original Contribution to Knowledge

This study is the first to investigate human robot proxemics in a systematic way, and in more depth than a simple interpretation in terms of social spatial zones along the lines of Hall (1968). The series of exploratory studies which investigated Human-Robot comfortable approach distances as the first part of the experimental work for this study are presented in Chapter 3. Many of these original results from these initial investigations have been published (cf. Walters et al. (2005a), Walters et al. (2007a), Walters et al. (2005b)) or in preparation (Walters et al. (2008).

To further investigate the underlying reasons for these results required original developments in HRI social theory, experimental methodology and expertise, and in ways to collect and analyse data. I was responsible for the original idea for developing a video-based experimental HRI trial methodology (cf. Woods et al. (2006), Woods et al. (2006a)) and originating, developing and implementing many of the key aspects, analytical and experimental methods for the methodology (cf. Walters et al. (2006), Walters et al. (2007)). This video based HRI methodology has now been adopted as one of the main means of evaluating the "user experience" aspects of robot systems developments for the COGNIRON Project European partner institutions. These Video-based HRI (VHRI) methodological developments and both the pilot and the subsequent verification studies and findings are presented in Chapter 4.

I found have found evidence confirming that a variety of factors including robot appearance, proxemic behaviour, context and situation have effects on human social perceptions of domestic robots. These initial findings from a VHRI study into peoples perceptions of consistency for robot attributes have been presented in a paper at the 2007 Artificial Life Conference (cf. Walters et al. (2007d)) and is currently in press as a journal article (cf. Walters et al. (2008a). Another original outcome from this part of the work is a novel application of an analytical method which was applied to quantify peoples relative ratings of various robot attributes and thus assess their perceptions for consistency of robot appearance and behaviours. Details can be found in Chapter 5.

In order to confirm and investigate a combination of various factors which had previously been found to affect HR proxemic behaviour a series of controlled live HRI trials were carried out. This is the first time that a controlled study had quantified and measured the relative contributions of a number of individual factors on human perceptions by means of their effects on human-robot proxemic preferences. The relevant results are presented in Chapter 6. and a paper is currently being prepared for publication based on some of these original findings (cf. Walters et al. (2008a)).

An original empirical framework is proposed in Chapter 7 in which these results can be unified in the wider context of a working theory of human-robot proxemics. This is seen as a necessary first step towards the desired end goal of creating and implementing a working robot proxemic system which can: a) exhibit socially acceptable social spatial behaviour when interacting with humans, b) interpret and gain additional valuable insight into a range of HRI contexts and situation from the relative proxemic behaviour of humans in the immediate area.

9.3 Future Work

The review in 9.1 identifies many areas where further investigations are required to either verify or obtain a more detailed coverage for a wider range of robot appearances, attributes, contexts and situations with regard to HR proxemics. The exploratory HRI experiments carried out for this thesis have produced a number of findings which inspire the generation of working hypotheses to explain. This inspired further more focussed experiments to confirm and extend these provisional results. There remain a number of open questions and issues, especially with regard to confirming, extending the range and quantifying the effect of robot non-verbal attributes with regard to HR proxemic behaviour.

There is a necessity for more experiments to gain data for approach distances and default values for HRI interpersonal distance preferences under wider range of HR contexts and situations. Also to perform these HRI experiments with a wider, and more finely graduated range of robot appearances and attributes and to investigate the use of alternative scales for rating robot appearances and other non-verbal attributes. In order to carry out these investigations in a systematic and repeatable way, it is seen as essential to implement the HR proxemic framework into a prototype automatic robot proximity control system for use in a systematic series of HRI trials to test, verify and improve the framework. It is hoped that this will lead eventually to a comprehensive theory for RH proxemics which will provide robots with both proxemic interpretive and control capabilities to enhance and facilitate interaction with users of domestic robots. This would be a contribution to achieving the eventual aim of a domestic robot that can be "socialised and personalized in order to meet the social, emotional and cognitive needs of people they are living with" as proposed by Dautenhahn (2004) and will be able to adapt itself accordingly (cf. Dautenhahn (2007)).

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Appendices

Appendix I: The Science Museum Interactive Games: Robot Program

I.I. The Main PeopleBot^{TM} Control Program: sm.py

The main robot control program for the Science Museum Interactive game uses a set of general functions for controlling the robot written to interface to the Pioneer ARIA API, contained in the import file bb.py. See next sub section I.II for more details. The program opens a console on a remote laptop PC, via ssh over the wireless network, so that the operator can control the robot.

```
# VICTEC Childrens Game Program for Robot
# Adapted for Science Museum visit
# M L Walters. 11 May 2004. Version 0.4.  18 Oct 2004, V 0.5


# first set up the python robot extensions and a few utilities
import bb
import os
from curses import *
from curses.wrapper import *

#Create a random number generator
import random
ran = random.Random(2)

#Now connect to the robot (bb)
bb.connect()
# Open the gripper (if it is not already)
bb.gripper.gripOpen()
bb.gripper.liftDown()
bb.gripperWait()
#Define a few useful objects from Aria
currentPose=bb.ArPose()
# Actions
acLimitForwards=bb.ArActionLimiterForwards("StopInFrontOfChild",750,1000,500)
bb.robot.addAction(acLimitForwards,50)
acTableLimiter=bb.ArActionLimiterTableSensor()
bb.robot.addAction(acTableLimiter,50)
acMoveForwards= bb.ArActionConstantVelocity("SelectVelocity",1000)
bb.robot.addAction(acMoveForwards,25)
# Do not move yet
bb.robot.deactivateActions()

# Global variables
cursesScr=0
noRounds = 6
songs=["djhel.mp3", "LondonBridge.mp3" ,"Super78.mp3",
       "Pussy.mp3", "TomTom.mp3", "Tweenies.mp3", "Year3000.mp3"]
#A couple of utility functions
def makeRandTurn():
       turnangle = ran.randrange(-1,2,2) * ran.randrange(20,175)
       turnvel=ran.randrange(900, 2200,400)
       bb.moveInc(0,turnangle,turnvel,1)
       #print "turnvel = ", turnvel
```

```
def makeRandPan():
	pantimes = ran.randrange(5,8)
	for n in range (1,pantimes):
		panangle = ran.randrange(-1,2,2) * ran.randrange(10,60)
		bb.look(panangle)
		bb.ArUtil.sleep(500)


#finally create the program as a function we can call at the interpreter command line
def pr(stepforward = 0, lookp=1, gripp = 1 ):
	"""
	This is the main program call that moves the robot in the first game
	victec.playround() with no options is no active camera or pointer, or step forward
	victec.playround(1) with active camera
	victec.playround (0,1) with active pointer, playround (1,1) both active
	Include a third parameter;- eg; victec.playround (1,1,500) to move forward/back to
	selected child
	"""
	#This is the main program that moves the robot for a round
	#print "Running ok"
	global cursesScr, noRounds
	try:
		while bb.gripper.getBreakBeamState() == 0:
			bb.say("I will need a  parcel in the basket to play this game please.")
			bb.ArUtil.sleep(10000)
		# play a song
		com=os.system("mpg123 "+ songs[ran.randrange(0,6)]+" &")
		#bb.Arutil.sleep(3000)
		stdscr.refresh()
		n = 0
		distance=0
		n1 = ran.randrange(10, 12)
		while n < n1:
			makeRandTurn()
			if lookp == 1:
				makeRandPan()
			n = n +1
		bb.look(0)
		# Manual control of selection;- uncomment next lines
		#bb.robot.setRotVel(15)
		#if cursesScr == 0:
		#	a = raw_input ("Press RETURN to stop")
		#else:
		#	stdscr.addstr(5,0,"Press any key to stop")
		#	n = stdscr.getch()
		bb.stop()
		com=os.system("killall -s9 mpg123")
		bb.ArUtil.sleep(500)
		bb.beep(2)
		# Then work the gripper if required
		if gripp != 0:
			bb.gripper.liftUp()
			bb.ArUtil.sleep(4000)
			bb.gripper.liftStop()
		#stdscr.addstr("killed")
		bb.say("Congratulations. You have been selected.")
		#bb.say("I am bringing your prize as fast as I can")
		#bb.ArUtil.sleep()
		if gripp != 0:
			bb.gripper.liftDown()
			bb.gripperWait()
			bb.ArUtil.sleep(3000)
		if stepforward != 0:
			bb.robot.setVel(1000)
```

```
                    bb.moveWait()
                    xpos=bb.robot.getX()
                    ypos=bb.robot.getY()
                    th=0 #bb.robot.getTh()
                    currentPose.setPose(0,0,th)
                    bb.robot.moveTo(currentPose)
                    bb.robot.clearDirectMotion()
                    # Enable these lines for actual game
                    acLimitForwards.activate()
                    acMoveForwards.activate() #Especially this one!
                    bb.ArUtil.sleep(500)
                    # Disable these lines for actual game
                    #if cursesScr == 0:
                    #      a= raw_input("Press Enter to return to centre")
                    #else:
                    #      stdscr.addstr(6,14,"Press any key to return to Centre")
                    #      n = stdscr.getch()
                    #      bb.stop()
                    #bb.ArUtil.sleep(500)
                    # End of variable code
                    while bb.robot.getVel()>5:
                          bb.ArUtil.sleep(100)
                    bb.stop()
                    while bb.gripper.getBreakBeamState() != 0:
                          bb.say("Please take the parcel")
                          bb.ArUtil.sleep(3000)
                    bb.say("Take off one wrapper layer only.")
                    if noRounds > 1:
                          while bb.gripper.getBreakBeamState() == 0:
                                bb.say("Please  replace  the  parcel  in  the  basket
please.")
                                bb.ArUtil.sleep(9000)
                          bb.say("Thankyou")
                    else:
                          bb.say("Congratulations and thankyou for playing with me")
                    # End of replacement
                    #bb.robot.deactivateActions()
                    bb.moveInc((-bb.robot.getX() * 0.99))
                    #print bb.robot.getX()
                    bb.moveWait()
                    #print     "X=",bb.robot.getX(),"          Y=",bb.robot.getY(),"
Th=",bb.robot.getTh()
                    #end of function
                    #except KeyboardInterupt:
                    if noRounds <= 1:
                          bb.say("Thankyou to everyone for playing with me.")
                    bb.stop()
      except KeyboardInterrupt:
            return


def cursesApp():
      global noRounds, cursesScr
      msg=""
      cursesScr=1
      noecho()
      cbreak()
      stdscr.keypad(1)
      #stdscr.nodelay(1)
      # Put code here
      while msg.lower() <> "q":
            # Messages to the screen
            stdscr.clear()
            curs_set(0)
            stdscr.addstr(0,20,"PEOPLEBOT CONTROL:")
            stdscr.addstr(1,16,"V0.6 M L Walters. Oct 2004")
            stdscr.addstr(3,0,"Press the following keys to operate the PeopleBot:")
            stdscr.addstr(4,0,"R = Run Revolute game    Q = Quit Control Program  W
= Wander")
            stdscr.addstr(5,0,"C  =  Goto  Centre/Start      Ctrl+C  =  Emergency  Stop
")
```

```
            stdscr.addstr(6,0,"
")
            stdscr.refresh()
            n = stdscr.getch()
            if (n<256) and (n>0):
                  msg = (chr(n ))
                  if msg.lower() == "r":
                        n = noRounds
                        while noRounds != 0:
                              stdscr.addstr(6,16,"Running      Revolute      game.
Round:")
                              stdscr.refresh()
                              print noRounds
                              pr(1)
                              noRounds = noRounds - 1
                        noRounds = n
                  elif msg.lower() == "w":
                        stdscr.addstr(6,5,"Running Wander Program. Press any key
to end   ")
                        stdscr.refresh()
                        bb.wander()
                        n = stdscr.getch()
                        bb.stop()
                  elif msg.lower() == "c":
                        stdscr.addstr(6,5,"Driving back to Home Position, Pres any
key to end   ")
                        bb.moveAbsXY(0,0)
                        n = stdscr.getch()
                        bb.stop()
                  #debug
                  #stdscr.addstr(10,5,chr(n))
                  #stdscr.refresh()
            stdscr.move(11,5)
            #print n,msg.lower()
      #end curses
      nocbreak()
      stdscr.keypad(0)
      echo()
      endwin()
      cursesScr=0
try:
      stdscr=initscr()
      cursesApp()
except KeyboardInterrupt:
      print "Stopping Robot and Program"
bb.end()
del bb.cam
```

I.II. The Python Import Functions for Controlling the PeopleBot™ Robot.

The file bb.py (see above) contains a number of useful Python functions for controlling the PeopleBot Robot. The listing is given below:

```
"""
Python Interface Extensions for Pioneer PeopleBot
M L Walters. June 2004.  V0.6. Changes October 2004 for SM visit.

This file contains some useful functions for programming and
```

```
interacting with the Pioneer PeopleBots using the Python wrapper
for the Aria robot API system
"""

# First import the required modules

# AriaPy requires that the _AriaPy.so shared object library is
# either in the current working directory or the appropriate python
# lib directory
from AriaPy import *

# Other standard Python modules with useful functions
import sys
import os
#Initialise the Aria system
Aria.init()


# Setup the robot with the various hardware bits attached
# Just insert # or remove to suit your PeopleBots configuration
robot = ArRobot()
gripper=ArGripper(robot)
cam=ArVCC4(robot, 0)
sonar=ArSonarDevice()
robot.addRangeDevice(sonar)
#laser=ArSick()
#Laser configure stuff to go here when/if we get one!

#Setup the robot port to connect to
# Either a Tcp port to the simulator or a remote robot
iPort= ArTcpConnection()
# or to the serial port on the local machine
conn = ArSerialConnection()
conn.setPort()

#Create the various behavious that may be required
acAvoidFrontNear=ArActionAvoidFront("Avoid Front Near",225,0)
acAvoidFrontFar=ArActionAvoidFront()
acAvoidSide=ArActionAvoidSide()
acBumpers=ArActionBumpers()
acStallRecover=ArActionStallRecover()
#acColorFollow=ArActionColorFollow()
acConstantVelocity=ArActionConstantVelocity()
acGoto=ArActionGoto()
goalPose=ArPose()
acStop=ArActionStop()
acTurn=ArActionTurn()
acLimiterForwards=ArActionLimiterForwards()
acLimiterBackwards=ArActionLimiterBackwards()
acLimiterTableSensor=ArActionLimiterTableSensor()

robot.addAction(acStallRecover,100)
robot.addAction(acBumpers,75)
robot.addAction(acAvoidFrontNear,50)
robot.addAction(acAvoidFrontFar,49)
robot.addAction(acConstantVelocity,25)
robot.addAction(acAvoidSide,39)
robot.addAction(acGoto,40)
robot.addAction(acTurn,25)
robot.addAction(acLimiterForwards,51)
robot.addAction(acLimiterBackwards,50)
robot.addAction(acLimiterTableSensor,52)
robot.deactivateActions()


def wander():
	robot.clearDirectMotion()
	acStallRecover.activate()
	acBumpers.activate()
	acAvoidFrontNear.activate()
	acAvoidFrontFar.activate()
```

```
        acAvoidSide.activate()
        acConstantVelocity.activate()

def stop():
        """
        Stops the robot.  Any physical movements are stopped and cancelled.
        """
        robot.deactivateActions()
        robot.stop()
        gripper.gripStop()
        gripper.liftStop()


def moveAbsXY(x=0,y=0):
        robot.clearDirectMotion()
        acStallRecover.activate()
        acBumpers.activate()
        acAvoidFrontNear.activate()
        acAvoidSide.activate()
        goalPose.setPose(x,y)
        acGoto.setGoal(goalPose)
        acGoto.activate()




def connect(socketno=0):
        """
        Initialises and connects to the robot.
        If socketno is 1 will connect to the simulator Tcp socket.
        If socketno is >1 then will connect to TCp socket: socketno
        Else if 0 or not given will connect to serial port
         unlock      """
        if socketno==0:
                robot.setDeviceConnection(conn)
        else:
                robot.setDeviceConnection(iPort)
        if (robot.blockingConnect() != 1):
                print "Could not connect to robot, exiting"
                disconnect()
                return 0
        #say("Connected okay")
        robot.runAsync(1)
        robot.enableMotors()
        print   "Robot   position   (",   robot.getX(),   ",",   robot.getY(),   ",",
robot.getTh(), ")"
        robot.unlock()
        cam.init()
        ArUtil.sleep(1000)
        print "Connected OK"

def void():
        """
        Dummy do nothing function
        """
        return

def end():
        """
        Stops the robot and then disconnects from the robot
        Shuts down Aria and cleans up as much as possible
        (Note: I have not found out how to stop the camera(object)
        at the local namespace level yet!!1)
        """
        robot.stop()
        robot.disconnect()
        Aria.shutdown()
        print "To exit Python cleanly type:\n\t del barbie.cam"
        print "Then press Ctrl + D to exit interpreter"
```

```
def look(panv=0,tiltv=0,zoomv=0,slewv=0):
	"""
	Moves and controls the robots camera
	All parameters optional and if called without will drive camera to:
		pan=0,tilt=0,zoom=0
	panv = pan angle (degrees). 0 = centre, +ve = left, -ve = right
	tiltv = tilt angle (degrees). 0 = level, +ve = up (90 max),m -ve = down(-30
min)
	zoomv = zoom in increments of 1/100 from 0 to 30000 (0 to 30x)
	slewv = camera slew rate in degrees per sec
	"""
	if slewv !=0:
		cam.panSlew(slewv)
		cam.tiltSlew(slewv)
	cam.pan(panv)
	cam.tilt(tiltv)
	cam.zoom(zoomv)

def moveWait():
	"""
	Waits for the robot to complete the previous programmed movement
	as specified by moveInc().  See moveInc for more details
	Note: You probably only need to call this function at the end of your program
	to allow the robot to complete it's last movement.
	"""
	while (robot.isMoveDone()==0) or robot.isHeadingDone()==0:
		# print "Waiting for move to finish"
		void()

def moveInc (distance=0, heading=0,vel=0,async=0):
	"""
	This causes the robot to move an Incremental distance in mm, at a relative
heading
	in degrees, at the specified vel(ocity) in mm per second.

	A moveInc may be synchronous (async=0):- the robot will turn by the heading
value,
	then move by the given distance in that order, or:

	A moveInc may be asynchronous:- the robot will turn and move by the given
heading
	simultaneously - the result will be a curved motion to achieve the given
heading.

	In both cases, the function will return before the move has been completed,
so that
	your Python program (or the interpreter) can do other things while the
movement is
	executing.

	The moveInc() function will always wait for the previous move to complete
before
	the specified move is started.  If the currnt move is to be replaced or
aborted
	use the stop() function to clear out any pending moves.
	"""

	moveWait()
	if vel != 0:
		robot.setVel(vel)
		robot.setRotVel(vel / 5 )
	robot.setDeltaHeading(heading)
	if async ==0:
		moveWait()
	robot.move(distance)

def moveIncXY(xval,yval,vel=0, async=0):
	"""
	This function is similar to moveInc, except the move is specified in terms of
	X and Y co-ords.  The Robots current heading is X = 0, and the robots
vel(ocity) is
```

```
        to be given in mm per second

        A moveInc may be synchronous (async=0):- the robot will turn by the heading
value        (degrees), then move by the given distance in that order, or:

        A moveInc may be asynchronous:- the robot will turn and move by the given
heading
        simultaneously - the result will be a curved motion to achieve the given
heading.

        In both cases, the function will return before the move has been completed,
so that
        your Python program (or the interpreter) can do other things while the
movement is
        executing.

        The moveInc() function will always wait for the previous move to complete
before
        the specified move is started.  If the current move is to be replaced or
aborted
        use the stop() function to clear out any pending moves.
        """
        print "Dummy"




def gripperInit():
        """
        Initialises the gripper and puts it in position to perform a pickUp()
operation
        If the gripper is closed, gripperInit() assumes that there is an object held
by
        the gripper, so first, it will perform a putdown operation to allow the
gripper
        to be made ready for a pickUp().
        """
        if (gripper.getPaddleState() != 0) or (gripper.getBreakBeamState() != 0) :
                gripper.liftDown()
                ArUtil.sleep(200)
                gripperWait()
        gripper.gripOpen()
        gripperWait()
        ArUtil.sleep(50)
        gripper.liftUp()


def gripperPark():
        """
        Puts the gripper into it's parking or storage position:- down with the
paddles
        closed.
        """
        gripperWait()
        gripper.liftDown()
        ArUtil.sleep(200)
        while (gripper.isLiftMoving()==1):
                #print "Lift moving down"
                void()
        #gripper.gripClose()

def gripperWait():
        """
        Waits for the gripper to complete a move or operation.   Useful for
synchronising
        other moves or sequences, or preventing the robot from moving off before the
        gripper has completed a pickUp() or putDown()
        """
        while (gripper.isLiftMoving()==1) or (gripper.isGripMoving()==1):
                #Print "Gripper moving"
                void()
```

```
def armPoint():
	gripper.liftUp()
	ArUtil.sleep(2200)
	gripper.liftStop()



def pickUp():
	"""
	Will pick up any object it finds as the gripper moves vertically downwards.
	If the paddle beams are broken or the paddles hit a solid surface, the
	vertical motion will stop and the paddles will close, hopefully picking up
	any object that is present. There is no way to directly verify if an object
	is in the gripper, other than the fact that the gripper is closed.
	"""
	gripperWait()
	if gripper.getPaddleState() == 0:
		gripper.liftDown()
		ArUtil.sleep(200)
		while gripper.isLiftMoving()==1 and gripper.getBreakBeamState() == 0:
			# print "Nothing to pick up yet"
			void()
		gripper.gripperHalt()
		gripper.gripClose()
		gripperWait()
		ArUtil.sleep(50)
		gripper.liftUp()


def putDown():
	"""
	Will put down any onbect held in the gripper paddles.  There is no way to
directly
	verify that there is an object in the paddles, only that they are closed.
	The gripper will move vertically downwards until a solid surface is touched.
	The gripper paddles will then open, allowing the held object to be released
	"""
	gripperWait()
	if gripper.getPaddleState != 0:
		gripper.liftDown()
		ArUtil.sleep(200)
		gripperWait()
		gripper.gripOpen()
		gripperWait()
		ArUtil.sleep(100)
		gripper.liftUp()


def say(textmsg="O K", pitch=150):
	"""
	This function speaks the text passed as a string parameter, enclosed within
quotes
	If supplied, the second parameter adjusts the pitch of the speaker
	"""
	msg = 'flite --setf int_f0_target_mean=' +str(pitch)+' "'+ textmsg +' " & '
	#print msg
	os.system(msg)

def beep(n=1):
	msg = 'echo -e "\a" > /dev/console'
	i = 0
	while i < n:
		os.system(msg)
		i = i + 1
		ArUtil.sleep(250)

#Friendly message if all goes well!!
print "Robot Python extensions loaded OK"
#say("Initialised okay")
```

Appendix II: Hardware for Humanoid Robot Arms

The pictures below shows more of the humanoid arms hardware details. These arms were made by me to fit on the PeopleBot™ for the RABE and LMFE HRI trials in chapters 5 and 6.

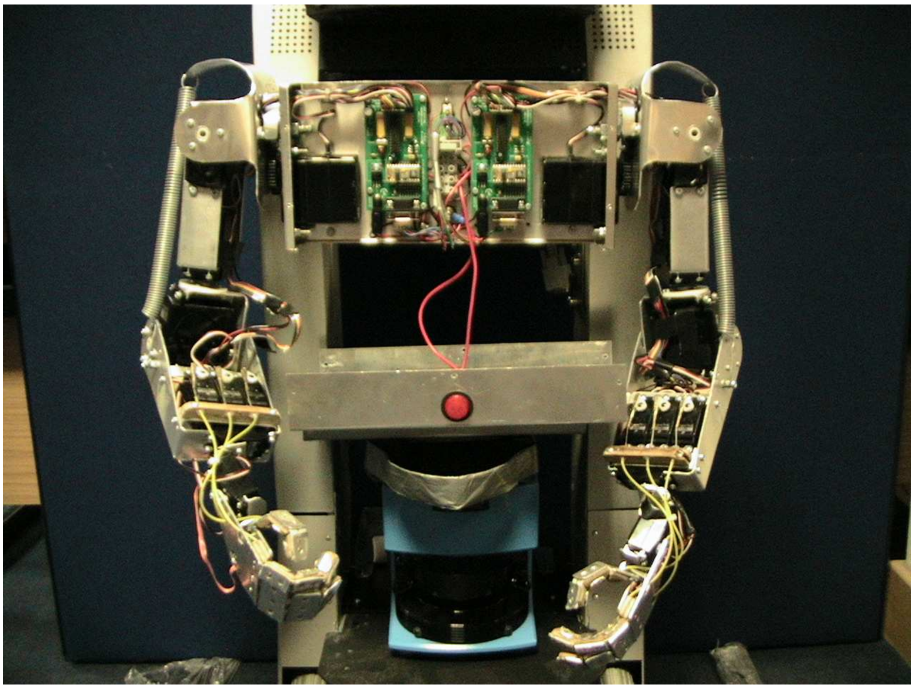


Figure 1. Illustration 1: View of humanoid arms with the main cover illustrating the general layout of components.

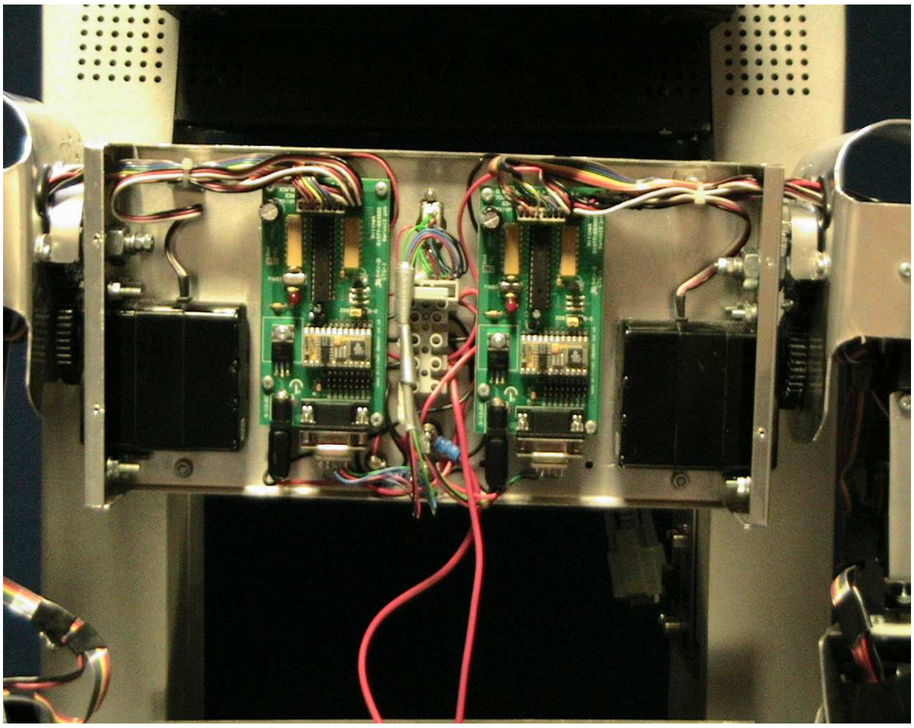


Figure 2. Illustration 2: Close up view of main assembly, showing dual Stamp BS2 controllers, base servo mountings and drive gear arrangement.

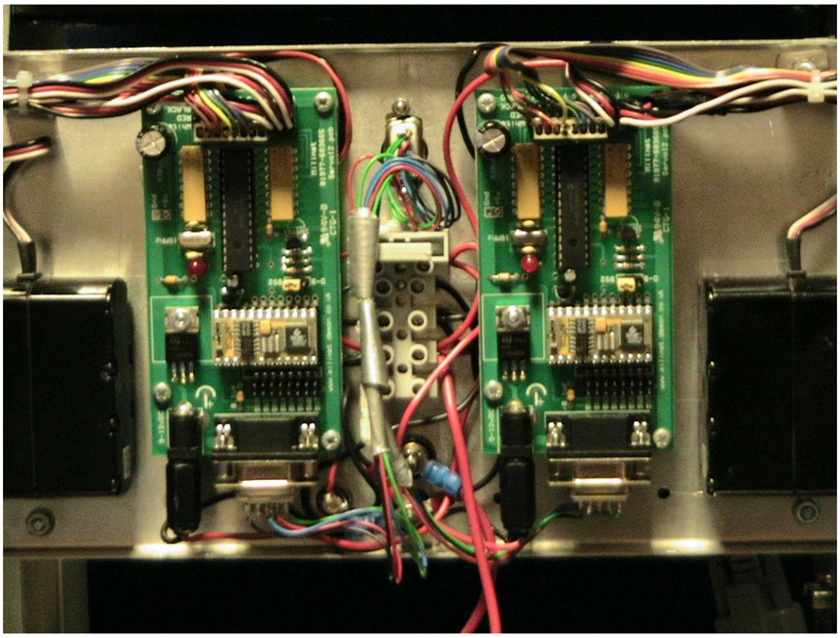


Figure 3. Illustration 3: Detain view of dual Stamp BS2 controllers

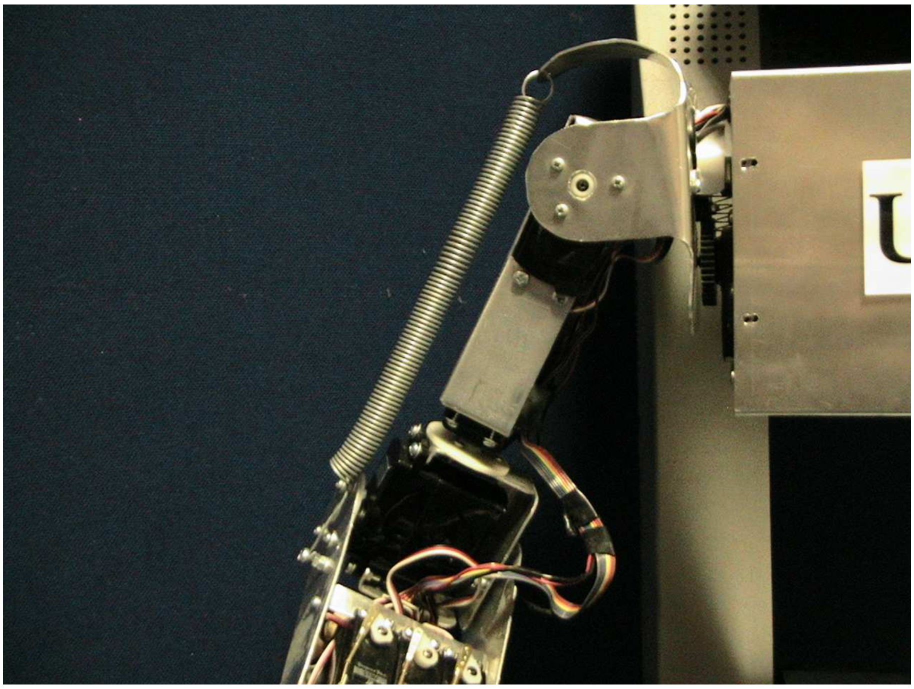


Figure 4. Illustration 4: Detail view of upper arm joints and servo drive arrangement

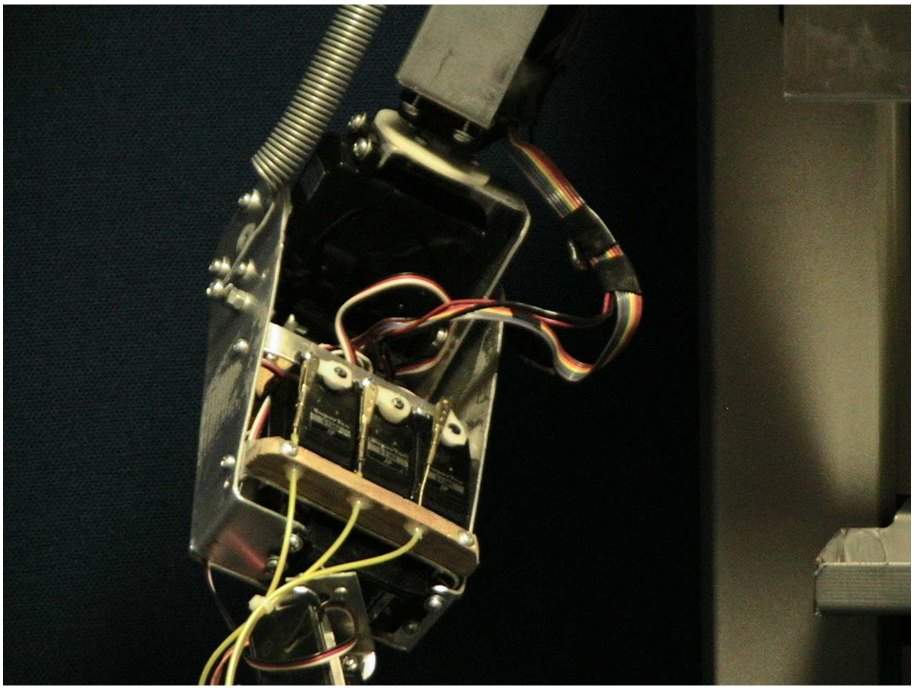


Figure 5. Illustration 5: Detail view of forearm, showing finger servos and and drive cables

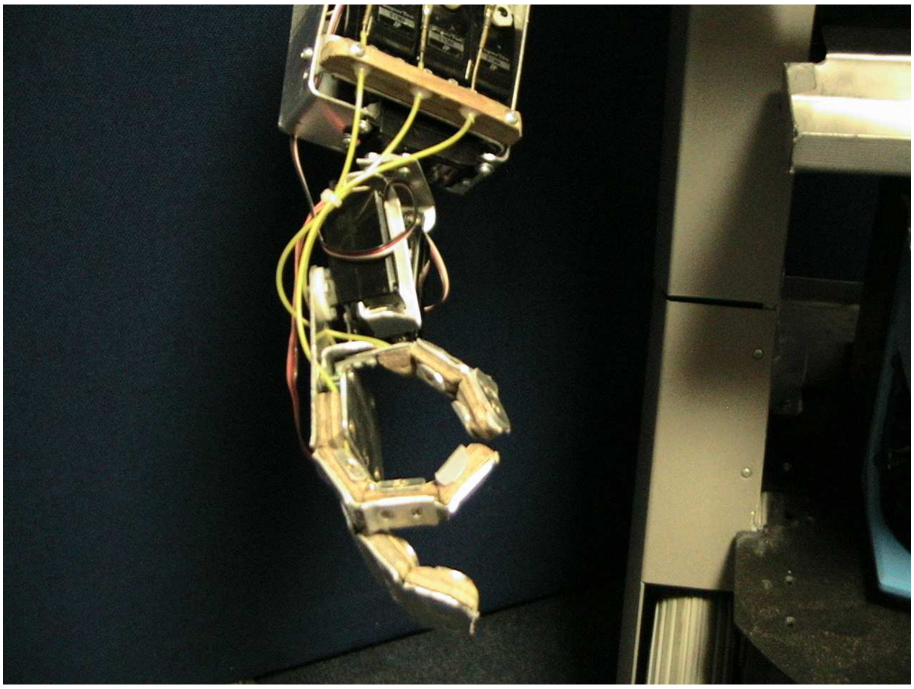


Figure 6. Illustration 6: Detail view of hand, showing wrist joints, fingers and thumbs

II.I. Arm Controller Firmware

The controllers firmware was programmed using the BS2P controllers built in programming language PBASIC. Both controllers received commands sent from a host in the form of ASCII text strings containing a simple one character address (R for Right arm, L for Left arm), then a single command character (J for move joint, M for move all joint together in coordinated motion), followed by a series of ASCII text coded numerical values as parameters if the command required additional information. The firmware program for both left and right arm controller was identical, apart from only responding to the commands that were prefixed with the appropriate address character. The print out is as follows:

```
'UH ASRG Robot Arm Firmware.
'(C) M L Walters. September 2005.
' V0.6. 4/11/5
' {$STAMP BS2P}
' {$PBASIC 2.5}
' {$PORT COM4}
'Variable declarations
' Current joint positions for arm
CurPosn VAR Byte(11)
' Current target joint positions.
```

```
EndPosn VAR Byte(11)
' Current gross arm joints veleocity
Vel     VAR Byte
Vel = 0' Number of increments to gain target position
Incs    VAR Byte
Incs = 0
' Index and tempory variable for input
n       VAR Byte
inchar  VAR Byte

'Constant declarations
'Right or left arm controller;- comment out as appropriate
Arm    CON "R" 'Right arm controller
'Arm   CON "L" 'Left arm controller
' Could also use for head or any other part controller e.g.
'Arm   CON "H"  'Head controller
start:
'Initialise the current position of the arm joints
PAUSE 1000
FOR n = 0 TO 10
  IF n = 3 AND Arm = "R" THEN
    CurPosn(n) = 220
  ELSEIF n = 3 AND Arm = "L" THEN
    Curposn(n) = 30
  ELSEIF n = 1 AND Arm = "R" THEN
    Curposn(n) = 110
  ELSEIF n = 1 AND Arm = "L" THEN
    Curposn(n) = 146
  ELSE
    CurPosn(n)= 128
  ENDIF
  SEROUT 11,16624,[255,n+32,Curposn(n)]
NEXT

' Wait for control message from host controller
DO
  'DEBUG CR, "OK",Arm
  ' Wait for a message for correct hardware address (Arm = "R" or "L")
  ' Otherwise ignore.
  ' Signal ready to accept new command
  SEROUT 16, 240,[Arm,"OK>",CR, LF,CR,LF] ' for BS2p
  ' Wait for command from host.
  DO
    'SERIN 16, 84,[inchar] ' for BS2
    SERIN 16, 240,[inchar] ' for BS2p
  LOOP UNTIL inchar = Arm
  'DEBUG Arm
  ' Then get command character
  SERIN 16,240,[inchar]
  ' Then carry out appropriate command.
  IF inchar = "?"  THEN
    ' Send all current positions back to the host
    SEROUT 16,240,["R,"]
    FOR n = 0 TO 10
      SEROUT 16,240,[DEC CurPosn(n),","]'[DEC CurPosn(n),","]
    NEXT
    'SEROUT 16,240,[DEC Vel,CR,LF]
  ELSEIF inchar = "J" THEN
    ' Move just the one joint
    SERIN 16,240,2000,Timeout,[DEC n, DEC Incs]
    SEROUT 11,16624,[255,n+32,Incs]
    ' Update the current position
    curPosn(n)= Incs
    'DEBUG "Joint ",DEC n,"Position", DEC Incs
  ELSEIF inchar = "M" THEN
    'DEBUG inchar
    ' Recieve a list of new positions, then move to the new positions
    FOR n = 0 TO 10
      SERIN 16,240,2000, Timeout,[DEC EndPosn(n)] ' or [EndPosn(n)]
      ' DEBUG EndPosn(n)
      GOTO NoTimeout
```

```
      Timeout:
      inchar=0
      EXIT
      NoTimeout:
      'DEBUG DEC EndPosn(n)
    NEXT
    IF inchar<>0 THEN
      SERIN 16,240,100, Timeout2,[DEC Vel]
      'DEBUG DEC Vel
      Timeout2:
      'DEBUG "**OK**",DEC Vel,"**"
      ' Check which joints to move and set up the interpolation increment counter
      'Note: IF 0, stay at current position.
      ' Move the arm in incrennments ?? change?. Need to watch for ESC/Stop from host
      'DEBUG CR, DEC Incs
      Incs = 1
      FOR n = 0 TO 10
        IF EndPosn(n)= 0 THEN
          EndPosn(n) = CurPosn(n)
        ELSEIF (EndPosn(n) > CurPosn(n)) THEN
          Incs = (EndPosn(n)- CurPosn(n)) MIN Incs
        ELSEIF CurPosn(n) > EndPosn(n) THEN
          Incs = (CurPosn(n)-EndPosn(n)) MIN Incs
        ENDIF
        'DEBUG CR,DEC CurPosn(n), TAB, DEC EndPosn(n), TAB, DEC Incs
        ' Incs now = the largest distance any joint has to move.
      NEXT
      ' Ignore velocity for now
      'IF Vel <> 0 THEN
        'Scale factor to be set empirically
        'Incs = (Incs/Vel/2) + 1
      'ENDIF
      IF Incs <> 0 THEN Incs = (Incs / Vel) + 1
      'Move the arm to the new position by co-ordinated P to P movement.
      DO WHILE Incs > 0
        'DEBUG CR
        'DEBUG "Interpolation Step ",DEC Incs, CR
        FOR n = 0 TO 10
          IF EndPosn(n)<> CurPosn(n) THEN
             IF (EndPosn(n) > CurPosn(n)) THEN
                CurPosn(n) = Curposn(n) + ((EndPosn(n)- Curposn(n))/Incs)
             ELSE
                CurPosn(n) = CurPosn(n) - ((Curposn(n) - EndPosn(n))/Incs)
             ENDIF
          ENDIF
          'Send the position to the servo controller
          'DEBUG TAB, DEC CurPosn(n)
          SEROUT 11,16624,[255,n,Curposn(n)]
          'put EMG Stop look for ESC serial input here
          ' serin with timeout etc
          ' Send watchdog/busy to host
          SEROUT 16, 240,["*"] ' for BS2p
            'SERIN 16,240,2, noESC,[inchar]   ' Adjust timeout here for gross speed
control?
          'DEBUG DEC inchar
          ' If an esc char received then stop immediatly
          'IF inchar=27 THEN EXIT
          'noESC:
        NEXT
        IF inchar=27 THEN EXIT
        Incs = Incs - 1
        'DEBUG CR
        ' otherwise carry on with the next joint
      LOOP
    ENDIF
  ELSE
    'do other stuff here?
  ENDIF
LOOP

'Debugging info/options - next three lines
```

```
'DEBUG CR,"D: String = ",STR inchar,CR 'Any BS inc BS2 & BS2P etc.
'SEROUT 16, 84,[CR,"Received: ",STR inchar,CR] ' for BS2
```

II.II. PC User GUI and API

The PC based host program is written in PYTHON and is in two main parts, implemented as two separate classes: The API is implemented as the class Robot Arm, and the GUI allows an non-programmer to access most of the functionality of the API by means of a user friendly GUI which was programmed using the platform independent Tkinter GUI tool kit, which is one of the standard libraries incorporated in a standard Python installation. The program has been tested and runs on Red Hat Fedora and Ubuntu Linux installations as well as Windows XP. It generates appropriately formatted ASCII command strings and sends them via a standard RS232 serial port to the robot arm controllers. The documentation is contained within the comments embedded within the code.

```
# TRAPS; Twin Robot Arm Programming System. Ported to Python 2.2
# (C) M L Walters. 9th May 2006
# V1.5 11/5/6


# Open necessary modules etc. These all standard ones.
from Tkinter import *  # for the gui for both Linux and windows.
from tkMessageBox import *
from tkSimpleDialog import *
from tkFileDialog import *
from string import *
from pickle import dump, load
from time import sleep
#  Needs  to  have  installed  pyserial  module  (will  then  work  under  linux  and
windows?!!!)
try:
    import serial
    serialAvail=1
    #print "serial ", serialAvail
except :
       print  "Pyserial  (maybe  also  ncluding  Win32api,  if  windows  version)  not
installed."
    print "Debug mode;- All arm output will go to console"
    serialAvail=0

# Initialise Global variables (could be constants? or obtain from setup frame/window
etc)
numJoints = 11   # Number of controled joints. Note; 11 joints = 0 to 10.
jointPosMin=1    # Maximum joint co-ord value
jointPosMax=255  # Minimum joint co-ord value
portAddress = 2 # 2 = 3rd serial port (eg. windows or dos; com3)


#
# First attempt to create a class for the arm path data + methods.
```

```
# Class should be a definition of an object called RobotArms
# Two classes defined here; the Robotarm API and the GUI part; TkTeacharm.
# The API can be used directly from any Python script and contains the main methods
# and values to operate the arm. The GUI class allows a non-programmer to access the
# object Robotarm in a user friendly way.
#

# Other essential variables - Updated automatically by TkTeacharm class Application
#   Current   joint   being   moved/taught   -   Tkinter   compatible   so   usage:
self.curMoveJoint.get() or .set()
# Current arm to be moved/taught - usage: self.currentArm.get() or .set()
# Number of steps in program can be obtained with len(Steplist[])= no of steps.

class RobotArm:
    """
     The RobotArm object contains methods for moving individual joints under host
program control, moving all
       joints  together  (interpoloted - co-ordinated point to point control) to
jointspace position. Also to learn,
    edit, replay, save and read routes composed of saved jointspace waypoints.
    """
    def __init__(self, portAddress=0, numJoints=11):
        #local variables
        self.right=1
        self.left=0
        self.numJoints=numJoints
        inchar = ""#
        self.ArmComm=0
        self.openSerPort(portAddress)
        # Main data lists (arrays).
         self.curRightPos = list(range(0,numJoints+2)) # Current right arm position
list
          self.curLeftPos = list(range(0,numJoints+2))  # Current left arm position
list
        self.curLeftVel = 4
        self.curRightVel= 4   # current velocity = 1 to 255(to be taught if T button
pressed.).
        self.curWait = 0       # current wait/dwell for current program step? -Spare
- Not implemented!!
        self.emg = 0        # emergency stop condition;- emg = 1
        # Main Data structures and indexes. StepList [stepNo][right/left][jointNo) =
JointPos
        # Set up the intial Step 0 taught positions (all zero)
        for n in range(0,numJoints+2):
            self.curLeftPos[n]=0
            self.curRightPos[n]=0
            #if n == 3:
            #    self.curLeftPos[n]= 0
            #    self.curRightPos[n]= 0
         self.curStepPos = [list(self.curLeftPos), list(self.curRightPos)] # Current
step positions (for step 0 = park/home position)
        self.StepList = list([self.curStepPos]) # 3D main data list "array". Usage:
StepList[stepNo][right/left] [jointNo]
        # Then the actual current arm "park" positions
          for n in range(0,numJoints):              # Set up initial (home) joint
positions
            self.curLeftPos[n]=128              # can be changed toconvenient values
as required
            self.curRightPos[n]=128
            if n == 1:
                self.curLeftPos[n]=140
                self.curRightPos[n]=112
            if n == 3:
                self.curLeftPos[n]= 30
                self.curRightPos[n]= 220
        # Initial velocities (not implemented)
        self.curLeftPos[numJoints]=self.curLeftVel
        self.curRightPos[numJoints]=self.curRightVel
        # Initial pauses between steps(not implemented to date)
        self.curLeftPos[numJoints+1]=0
        self.curRightPos[numJoints+1]=0
```

```
        # Then the main index variables
         self.curStep = 0                              # Current step being taught -
index into Steplist[][][].
        self.maxStep=0                              # Number of steps in program.
        # then set the intial home position;- can  be changed if required
        self.teach("Replace", 0)
        self.executeSteps(0,0)
        #print StepList

    def openSerPort(self,PortAddress):
        """
        Opens the serial port at Port address. PortAddress may be an
         integer (0,1,2 etc.) or an actual path address (e.g. "com1", (/dev/usbser0)
etc.)
        Note: serial port 0 = "com1" for MSDos sytems.
        #print portAddress, type(portAddress)
        """
        # Initialise serial port
        # Open serial device
        #print "portAddress = ", portAddress
        if isinstance(portAddress, int):
            print "Port number = int =",PortAddress
            try:
                                                  self.ArmComm=serial.Serial(PortAddress,
9600,xonxoff=0,rtscts=0,timeout=.01)
                self.serialAvail=1
            except:
                self.serialAvail=0
        elif isinstance(portAddress,str):
            print "Port device path = ", PortAddress
            try:
                               self.ArmComm=serial.Serial(PortAddress,9600,xonxoff=0,
rtscts=0,timeout=.01)
                self.serialAvail=1
            except:
                self.serialAvail=0
        else:
            self.serialAvail=0
        if self.serialAvail==0:
            print "Serial port not available."
        else:
            print " Serial port available:= ",self.serialAvail
        # Send a message to the port to check it is ok
        # self.ArmComm.write("xxxxx")
        # flush out echoed characters
        #self.ArmComm.flushOutput()
        if self.serialAvail != 0:
            self.ArmComm.flushInput()
        #print "Flush 1= ",inchar

    def closeSerPort(self):
        """
        Closes the serial port
        """
        if self.serialAvail != 0: self.ArmComm.close()

    def stopArm(self):
        print "Stop Called"
        self.emg = 1
        if self.serialAvail != 0:
            self.ArmComm.flushOutput()
            self.ArmComm.write(chr(27)+ chr(27) + chr(27) + chr(27) + chr(27))


    def sendSer (self,msg = ""):
        """
        Sends msg to device on serial port.
        Adds chr(13) to end of string.
        """
        inmsg="*"
```

```
          # Wait for previous move to finish;- arm will send "*" every 100ms or so
while moving
        if self.serialAvail != 0:
            self.ArmComm.flushInput()
            self.ArmComm.timeout = .1
            while inmsg != "":
                inmsg = self.ArmComm.readline()
                # print inmsg,
            # Then send the commmand, adding a cr+lf to the string.
            for n in range(len(msg)):
                self.ArmComm.write(msg[n])
                inmsg = self.ArmComm.read(1)
                # Note; This statement needs to be in to slow things down.
                # Need a better method here?? How to delay for a few ms?
                  sleep(.001) # This is ok for compiled version. Maybe look at again
some time?
                #print msg[n],
                #print "",
                #print "",
            self.ArmComm.write(chr(13)+chr(10))
        else:
            print msg,

    def jointMove(self,armNo,jointNo, position):
        # updates the global current positions variables
        # self.curRightPos, self.curLeftPos
        commandStr =""
        print
        if ((position > 0) and (position < 256)) and (self.serialAvail == 1):
            if armNo == self.right:
                self.curRightPos[jointNo]=position
            else:
                self.curLeftPos[jointNo]=position
            # then move arm - put code here
            if self.serialAvail == 1:
                # debug stuff
                #inchar = self.ArmComm.readline()
                #print "Flush 1= ",inchar
                if armNo == self.right:
                    #print " RM "
                    commandStr = "RJ" + str(jointNo)+ " " + str(position)
                    #self.sendSer("RJ")
                    #print inchar
                elif armNo == self.left:
                    #print " LM "
                    commandStr = "LJ" + str(jointNo)+ " " + str(position)
                    #self.sendSer("LJ")
                    #print inchar
                self.sendSer(commandStr )
            else:
                print "ArmNo=", armNo,"JointNo=",jointNo,"Position=",position
        self.emg = 0

    def armMove(self,armNo=0,positionList=0):
        """
        Move all joints of one arm in coordinated point to point movement.
        If positionList = 0 will move to the current step postion as contained in
           the currently (loaded) step sequence. Otherwise will move to a position
defined
        by a list of the form; positionList[ j0 j1 j2 ... jn]
        """
        #global StepList
        #print "Arm move:- ArmNo=","Position=",positionList
        commandStr = ""
        if positionList == 0:
            # get the current step positions for armNo for left or right.
            positionList = list(self.StepList[self.curStep][armNo])
            # print "default current step",self.StepList[self.curStep][armNo]
        if armNo == self.left:
            # Send correct prefix to arm;
            self.curLeftPos = list(positionList )
```

```
            commandStr = "LM"
        else:
            self.curRightPos = list(positionList)
            commandStr = "RM"
        # Then send the correct list of positions.
        for n in range(len(positionList)):
                commandStr = commandStr + chr(positionList[n]) #commandStr + " " +
str(positionList[n])
            #self.sendSer(str(positionList[n])+ chr(13))
            #print positionList[n],
        #print commandStr
        self.sendSer(commandStr)
        self.emg = 0

    def armsMove(self, leftPosList=0, rightPosList=0):
        """
        Move all joints of both arms in coordinated point to point movement.
         If LeftPosList or rightPosList = 0 will move to the current left/right step
postions as contained in
          the currently (loaded) step sequence. Otherwise will move to a position
defined
        by a list of the form; positionList[ j0 j1 j2 ... jn]
        """
        commandStr = ""
        if leftPosList == 0:
            # get the current step positions for armNo for left.
            leftPosList = list(self.StepList[self.curStep][self.left])
        if rightPosList == 0:
            # get the current step positions for armNo for right.
            rightPosList = list(self.StepList[self.curStep][self.right])
        # Send correct prefix + position list to left arm;
        self.curLeftPos = list(leftPosList )
        commandStr = " LM"
        for n in range(len(leftPosList)):
            commandStr = commandStr + chr(leftPosList[n]) #" " + str(leftPosList[n])
        # Then Send correct prefix + position list to right arm;
        self.curRightPos = list(rightPosList)
        commandStr = commandStr + chr(13)+ chr(10) + " RM"
        for n in range(len(rightPosList)):
                    commandStr = commandStr + chr(rightPosList[n])#" " +
str(rightPosList[n])
        #print commandStr # debug
        self.sendSer(commandStr)
        self.emg = 0

    def home(self):
        """
        drives the arms to the "Park" position. Same as executeSteps(0,0)

        """
        self.cursStep=0
        self.executeSteps(0,0)

    def executeSteps(self, fromStep=0, toStep=-1):
        """
        This function executes a range of steps saved in the array StepList.
        Usage executeSteps([fromStep],[toStep].
        If fromStep is ommited execution will start from step 0
        If toStep ommitted, willexecute to the maxStep in the list
        """
        # Check in range
        if toStep < 0:
            toStep=self.maxStep
        if fromStep >=0 and fromStep <=self.maxStep and toStep<=self.maxStep:
            # and serial port is open
            if self.serialAvail==1:
                # then run the arm step sequence
                # print "Executing from: ",fromStep, " to: ",toStep
                for n in range(fromStep, toStep + 1):
                    print
                    print "Executing Step ", n
```

```
                    if self.emg == 1:
                        break
                        self.armsMove(self.StepList[n][self.left], self.StepList[n]
[self.right])
            else:
                # Debug:- print to console
                print "Error", self.StepList[fromStep - toStep]
        else:
            print "Bad step numbers"
        if self.emg == 1:
            self.emg = 0
            print "Interupted"
        else:
            print "OK"



    def clearData(self):
        #global StepList, curStep, maxStep
        #print len(StepList)
        for n in range(self.maxStep,0,-1):
            #print "*",n
            del self.StepList[n]
        self.curStep = 0   # Current step being taught - index into Steplist[][][].
        self.maxStep = 0   # top of steplist
        #print "cleared" , len(StepList)

    def saveArmData(self, filename=""):
        #print "Saving StepList"
        #global StepList
        saveFile=open(filename,"w")
        dump(self.StepList, saveFile)
        saveFile.close()
        return filename

    def openArmData(self, filename=""):
        #global StepList, curStep, maxStep
        #print "Opening data"
        openFile=open(filename,"r")
        self.StepList=load(openFile)
        openFile.close()
        self.maxStep=len(self.StepList)-1
        self.curStep=self.maxStep
        return filename

     #Here are the main StepList editing commands functions called from the user or
GUI application
    # Maybe package nicely into a "gesture" object???
    def teach(self, mode = "Insert", stepNum=-1):
        """
        Saves the current position at stepNum.
        Mode can be either (R)eplace or (I)nsert. Default is Insert.
         Insert always preserves existing steps.  Replace overwrites the current step
values.
          If at the end of the program, or StepNum=-1, a new step is created on the
end of the
             sequence, and the sequence extended if mode is Insert. Insert also
increments curStep
        if it is at the top of the program.
        """
                                                              print        "Teaching",
self.curStep,"***Left",self.curLeftPos,"**Right",self.curRightPos
        # check to see if step number to teach is explicitly provided
        if (stepNum > -1) and (stepNum < self.maxStep):
            self.curStep=stepNum
        #else:
        #    return "Out of Range"
        #Then mode and appropriate action.
        #print "XX", curStep
        if (mode == "Insert")or (mode == "I"):
            if stepNum > self.maxStep :
```

```
                                        self.StepList.append([list(self.curLeftPos),
list(self.curRightPos)])
            else:
                            self.StepList.insert(self.curStep,[list(self.curLeftPos),
list(self.curRightPos)])
        elif mode == "Replace" or (mode == "R"):
            # special case at EOP - do nothing
            # if self.curStep<=self.maxStep:
                                  self.StepList[self.curStep]=[list(self.curLeftPos),
list(self.curRightPos)]
        # Update the number of steps in the Steplist.
        self.maxStep = len(self.StepList)-1 # As the index into Steplist counts from
0
        #print "Taught StepList"
        #print StepList

    def stepDelete(self, stepNum=-1):
        #global numJoints, StepList, curStep, maxStep,right,left
        if stepNum > -1 and stepNum <= self.maxStep:
            self.curStep=stepNum
        if self.curStep < self.maxStep and self.maxStep>0:
            del self.StepList[self.curStep]
            self.maxStep = self.maxStep-1
        #print "delete StepList",StepList,"MaxStep=",maxStep,"curStep=",curStep
        #print StepList

    def armPortClose(self):
        self.ArmComm.close()




# Setup the main Tkinter GUI display application class for manipulating the gesture
object/class using Tkinter

class TkTeachArm(Frame):
    """
    The main GUI for non-programmers to develop movements for the robot arms.
    Works under windows and Linux (so long as an xserv is running. It will also run
remotely).

    """
    def __init__(self, RobArms, master=None):
        Frame.__init__(self, master)
        # first important variables
        self.Arm=RobArms # This allows access to the RobotArm object locally within
methods
        self.right=1
        self.left=0
        self.prevPosition=0
        self.master.title("TRAPS. V1.5. M L Walters. 2006")
        print self.Arm.curStep
        self.grid()
        self.createWidgets()
        #self.updateDisplay()
        #self.updateMoveCurrent()

    def createWidgets(self):
        # Control variables - all Tkinter Var types, so use .get() and .set() to
manipulate.
        self.curMoveJoint = IntVar() # Current joint to move 0 to numJoints
        self.curStepNumStr = StringVar() # TK control variable to display current
step number
        self.currentArm = IntVar() # right=1, left=0
        self.scaleValue = IntVar() # 1 to 255. 0 = no move. From slider input.
        # joint position control variable = StringVar Type for Tkinter display only
        self.jointTaughtPosVar= list(range(0, numJoints+2)) # for displayinmg the
arm taught positions.
            self.jointCurPosRightVar = list(range(0,numJoints+2)) # displaying the
current arm joint positions
```

```
          self.jointCurPosLeftVar = list(range(0,numJoints+2))   # and the left arm
joint positions.
        for n in range(0,numJoints+2):
            self.jointTaughtPosVar[n]= StringVar()
            self.jointCurPosRightVar[n] = StringVar()
            self.jointCurPosLeftVar[n] = StringVar()
        # lists for the joint position/selection widgets
        self.jointLabel = list(range(0,numJoints))
        self.jointButton = list(range(0, numJoints))
        self.jointTaughtPosLabel = list(range(0,numJoints+2))
        self.leftPosLabel = list(range(0, numJoints+2))
        self.rightPosLabel = list(range(0, numJoints+2))
        # create the widgets and attach the approppriate keypress events
        self.quitButton = Button(self, text = "Quit",border=5, bg="Yellow",command =
self.quitApplication,underline=0,takefocus=0)
        self.bind_all("Q",self.quitApplication)
        self.bind_all("q",self.quitApplication)
            self.clearButton  =  Button(self,  text  =  "Clear",border=5,  bg="Yellow",
command = self.clearAll,underline=0,takefocus=0)
        self.bind_all("C",self.clearAll)
        self.bind_all("c",self.clearAll)
                                            self.saveButton     =     Button(self,
text="Save",border=5,bg="Yellow",underline=0,takefocus=0,command=self.saveFile)
        self.bind_all("S",self.saveFile)
        self.bind_all("s",self.saveFile)
                                            self.openButton     =     Button(self,
text="Open",border=5,bg="Yellow",underline=0,takefocus=0, command=self.openFile)
        self.bind_all("O",self.openFile)
        self.bind_all("o",self.openFile)
                                            self.nextButton     =     Button(self,
text="Next",border=5,bg="Yellow",underline=0,takefocus=0, command = self.setNext)
        self.bind_all("N",self.setNext)
        self.bind_all("n",self.setNext)
                                            self.prevButton     =     Button(self,
text="Previous",border=5,bg="Yellow",underline=0,takefocus=0,       command       =
self.setPrev)
        self.bind_all("P",self.setPrev)
        self.bind_all("p",self.setPrev)
                                            self.gotoButton     =     Button(self,
text="Goto",border=5,bg="Yellow",underline=0,takefocus=0, command = self.setGoto)
        self.bind_all("G",self.setGoto)
        self.bind_all("g",self.setGoto)
                                            self.homeButton     =     Button(self,
text="Home",border=5,bg="Yellow",underline=0,takefocus=0, command = self.setHome)
        self.bind_all("H",self.setHome)
        self.bind_all("h",self.setHome)
         self.teachButton = Button(self, text="Replace",border=5,bg="Yellow",command
= self.doReplace,underline=0,takefocus=0)
        self.bind_all("T",self.doReplace)
        self.bind_all("t",self.doReplace)
                                             self.delButton     =     Button(self,
text="Delete",border=5,bg="Yellow",underline=0,takefocus=0, command= self.doDelete)
        self.bind_all("D",self.doDelete)
        self.bind_all("d",self.doDelete)
                                          self.insertButton     =     Button(self,
text="Insert",border=5,bg="Yellow",underline=0,takefocus=0, command=self.doInsert)
        self.bind_all("I",self.doInsert)
        self.bind_all("i",self.doInsert)
                                            self.moveButton     =     Button(self,
text="Move",border=5,bg="Yellow",underline=0,takefocus=0, command=self.move)
        self.bind_all("M", self.move)
        self.bind_all("m", self.move)
                                             self.runButton     =     Button(self,
text="X=eXecute",border=5,bg="Yellow",takefocus=0, command=self.doExecute)
        self.bind_all("X", self.doExecute)
        self.bind_all("x", self.doExecute)
                                             self.escButton     =     Button(self,
text="SPACE=Stop",border=5,bg="Yellow",takefocus=0,command=self.emgStop,
                                disabledforeground="Blue")
        self.bind_all("<space>", self.emgStop)
        # debug facilty - see what StepList is at any time
```

```
        #self.bind_all("m", self.showStepList)
        # place on the Application Frame
        self.columnconfigure(0,minsize = 60)
        self.rowconfigure(0,minsize=5)
        #self.rowconfigure(1,minsize= 20)
        #self.rowconfigure(2,minsize= 20)
        #self.rowconfigure(3,minsize= 20)
        #row 1
        self.quitButton.grid(row=1,column=0,ipadx=20,padx=20)
        self.clearButton.grid(row=1,column=1,ipadx=19)
        self.saveButton.grid(row=1,column=2,ipadx=20)
        self.openButton.grid(row=1, column=3,ipadx=20)
        #row 2
        self.nextButton.grid(row=2, column=0,ipadx=18)
        self.prevButton.grid(row=2, column=1,ipadx=8)
        self.gotoButton.grid(row=2, column=2,ipadx=21)
        self.homeButton.grid(row=2, column=3,ipadx=16)
        #row 3
        self.teachButton.grid(row=3, column=0,ipadx=6)
        self.insertButton.grid(row=3, column=1,ipadx=17)
        self.delButton.grid(row=3, column=2,ipadx=16)
        self.moveButton.grid(row=3, column=3,ipadx=19)
        #row 4
        self.runButton.grid(row=4, column=0,ipadx=32,pady=2, columnspan=2)
        self.escButton.grid(row=4, column=2,ipadx=22,pady=2, columnspan=2)
        # Show the arm joint positions
        #Column headings
        #self.topText1=Label(self,text="Keys: 0 to "+str(numJoints-1)+
         #                       " select Joint to move, V to set velocity, R and L
select Arm, -> and <- to move",
        #                    relief=SUNKEN,border=5)
        #self.topText1.grid(row=7,column=0,columnspan=4,pady=2,ipadx=2)
                        self.jointTitleLabel1   =   Label(self,   text="Joint   to
Move",relief=RIDGE,bg="Yellow",border=5,takefocus=0)
        self.jointTitleLabel1.grid(row = 8, column=0, pady=5)
                            #self.jointTitleLabel2    =    Label(self,    text="L/R
ArmPosition",relief=RIDGE,bg="Yellow",border=5,takefocus=0)
        #self.jointTitleLabel2.grid(row = 8, column=1)
        # Show Arm select buttons/headings
        self.currentArm.set(self.right)
                  self.armLeftButton  =  Radiobutton(self,  text="Left  Arm  Move",
variable=self.currentArm, value=self.left,
                                                            relief=RAISED, border=5,
bg="Yellow",command = self.updateDisplay,
                                         takefocus=0)
        self.armLeftButton.grid(row = 8, column=1)
                 self.armRightButton  =  Radiobutton(self,  text="Right  Arm  Move",
variable=self.currentArm,value=self.right,
                                                            relief=RAISED, border=5,
bg="Yellow",command = self.updateDisplay,
                                          takefocus=0)
        self.armRightButton.grid(row = 8, column=2)
                  self.jointTitleLabel2  =  Label(self,  text="Taught  Pos\n  Left
Right",relief=RIDGE,bg="Yellow",
                                      border=5)
        self.jointTitleLabel2.grid(row = 8, column=3)
        # Show the Joint buttons and positions (all 128= home/start position)
        self.curMoveJoint.set(0)
        for n in range(0,numJoints):
            # Show the current arm joint sected to move
                             self.jointButton[n]=Radiobutton(self,  text="Joint  "+
upper(replace(hex(n),"0x","")),
                                              variable=self.curMoveJoint, value=n,
                                              relief=RAISED, border=5, bg="Yellow",
                                                                         command  =
self.jointSelect,underline=6,takefocus=0)
            #if n < 10:
            #    self.jointButton[n].grid(row=n+9,column=0, ipadx=7)
            #else:
            self.jointButton[n].grid(row=n+9,column=0,ipadx=3)
            # Then the position labels
```

```
            # Actual position labels (to be updated regularly?)
            # Control variable: self.jointTaughtPosVar[n]=StringVar()
                         self.jointTaughtPosVar[n].set(str(self.Arm.curLeftPos[n])+"
"+str(self.Arm.curRightPos[n]))
                                                      self.jointTaughtPosLabel[n]    =
Label(self,textvariable=self.jointTaughtPosVar[n])
            self.jointTaughtPosLabel[n].grid(row=n+9,column=3)
                                                  self.leftPosLabel[n]=    Label(self,
textvariable=self.jointCurPosLeftVar[n])
            self.jointCurPosLeftVar[n].set(self.Arm.curLeftPos[n])
            self.leftPosLabel[n].grid(row=n+9, column=1)
                                                 self.rightPosLabel[n]=    Label(self,
textvariable=self.jointCurPosRightVar[n])
            self.jointCurPosRightVar[n].set(self.Arm.curRightPos[n])
            self.rightPosLabel[n].grid(row=n+9, column=2)
        # Then the velocity and wait buttons
                                           self.velButton     =     Radiobutton(self,
text="Velocity",variable=self.curMoveJoint, value=(numJoints),
                                                 relief=RAISED, border=5,bg="Yellow",
command=self.jointSelect,
                                    underline=0,takefocus=0)
        self.velButton.grid(row=numJoints+11, column=0,ipadx=0)
         # Show the actual velocity values (treated as just another joint position
here)
         self.jointTaughtPosVar[numJoints].set(str(self.Arm.curLeftPos[numJoints])+"
"+str(self.Arm.curRightPos[numJoints]))
                                           self.jointTaughtPosLabel[numJoints]     =
Label(self,textvariable=self.jointTaughtPosVar[numJoints])
                                        self.leftPosLabel[numJoints]=     Label(self,
textvariable=self.jointCurPosLeftVar[numJoints])
        self.leftPosLabel[numJoints].grid(row=numJoints+11, column=1)
                                         self.rightPosLabel[numJoints]=     Label(self,
textvariable=self.jointCurPosRightVar[numJoints])
        self.rightPosLabel[numJoints].grid(row=numJoints+11, column=2)
        self.jointCurPosLeftVar[numJoints].set(self.Arm.curLeftPos[numJoints])
        self.jointCurPosRightVar[numJoints].set(self.Arm.curRightPos[numJoints])
         self.jointTaughtPosVar[numJoints].set(str(self.Arm.curLeftPos[numJoints])+"
"+str(self.Arm.curRightPos[numJoints]))
                                           self.jointTaughtPosLabel[numJoints]     =
Label(self,textvariable=self.jointTaughtPosVar[numJoints])
        self.jointTaughtPosLabel[numJoints].grid(row=numJoints+11,column=3)
                                    #     self.waitButton     =     Radiobutton(self,
text="W=Wait",variable=self.curMoveJoint, value=numJoints+2,
        #                         relief=RAISED, border=5,bg="Yellow")
        # self.waitButton.grid(row=numJoints+11, column=0,ipadx=2)
        # Create a scale widget
        self.scaleValue.set(128)
        self.jointmoveScale = Scale(self,variable=self.scaleValue,from_=1,to=255,
                                    orient=HORIZONTAL, length=250,
                                         label="Set value using -> <- arrow keys or
mouse",
                                         relief=RIDGE, border=5, troughcolor="blue",
bg="Yellow",
                                                     activebackground="Red", command =
self.updateMoveCurrent)
         self.jointmoveScale.grid(row=numJoints+12, column=1,columnspan=2, padx=10,
pady=5)
        self.jointmoveScale.focus_set()
        # Put in the Step counter
        self.curStepNumStr.set(str(self.Arm.curStep))
        self.curStepLabel = Label(self,text="Step               ", border=5,
                                  relief=RIDGE, bg="Yellow")
                                   self.curStepLabel.grid(row=numJoints+12,column=3,
ipady=22,ipadx=20,padx=20,sticky=W, columnspan=2)
                               self.currentStepEntry    =    Entry(self,    width=5,
textvariable=self.curStepNumStr,takefocus=0)
        self.currentStepEntry.grid(row=numJoints+12, column=3, sticky=E)
        # Get the serial device to use from the user
        #serError=-1
        #while serError== -1:
```

```
          #     serialPort=askinteger("TRAPS V0.9. Serial Device Select","Enter port
number or device name: ",
        #                     initialvalue=2,parent=self)
        #    serError=openArmDevice(serialPort)

    def showStepList(self,keypress=""):
        """
        Debuginng facilty - remove from final program
        """
        #global self.Arm.StepList
        print self.Arm.StepList

    # Implement the methods which call the correct StepList editing functions
    def quitApplication(self,keypress=""):
        """
        Put some confirnation code in here?  as well??
        """
        self.quit()

    def saveFile(self,keypress=""):
        filename= asksaveasfilename()
        self.Arm.saveArmData(filename)

    def openFile(self, keypress=""):
        filename = askopenfilename()
        self.Arm.openArmData(filename)
        self.updateDisplay()

    def doReplace(self,keypress=""):
        self.Arm.teach("Replace")
        self.updateDisplay()

    def doInsert (self,keypress=""):
        #global curStep,maxStep
        self.Arm.teach("Insert")
        self.updateDisplay()
        # Special case, increment current step variable if at top of program
        if self.Arm.maxStep == self.Arm.curStep+1:
            self.Arm.curStep = self.Arm.curStep+1
        #need a pause here ??
        self.updateDisplay()


    def clearAll(self,keypress=""):
        self.Arm.clearData()
        self.updateDisplay()

    def doDelete(self, keypress=""):
        self.Arm.stepDelete()
        self.updateDisplay()

    def setNext(self, keypress=""):
        """
        """
        #global curStep, maxStep
        if self.Arm.curStep < self.Arm.maxStep:
            self.Arm.curStep = self.Arm.curStep + 1
        self.updateDisplay()

    def setPrev(self, Keypress=""):
        """
        """
        #global curStep
        if self.Arm.curStep > 0:
            self.Arm.curStep = self.Arm.curStep-1
        self.updateDisplay()

    def setHome(self,keypress=""):
        """
        """
        self.Arm.curStep = 0
```

```
        self.updateDisplay()

    def setGoto(self, keypress=""):
        """
        Use the tk requester to get the step number from the user
        """
        # get number from user
        #global curStep
        inputNum = askinteger("User Input","Step number to make current: ")
        #print "input",inputNum
         if (inputNum <> "None") and (inputNum <= self.Arm.maxStep) and inputNum >=
0:
            self.Arm.curStep=inputNum
            #print curStepQ
        self.updateDisplay()

    def move(self,keypress="",):
        """
        """
        # Put move to current step stuff in here
        #self.Arm.armMove(0)
        #self.Arm.armMove(1)
        self.Arm.armsMove()
        self.updateDisplay()

    def doExecute (self, keypress=""):
        self.Arm.executeSteps()
        self.updateDisplay()
        # print self.Arm.StepList

    def emgStop(self, keypress=""):
        print "EMG STOP"
        self.Arm.stopArm()

    # Various utility and housekeepng methods for the GUI display
    def jointSelect(self):
        """
        sets the slider scale to the selected joints position.
        Also highlights the current joint to move number reading
        """
        for n in range(0,numJoints+1):
            self.leftPosLabel[n].config(bg="grey",fg="black")
            self.rightPosLabel[n].config(bg="grey",fg="black")
        if self.currentArm.get()== self.right:
            self.scaleValue.set(self.Arm.curRightPos[self.curMoveJoint.get()])
            self.rightPosLabel[self.curMoveJoint.get()].config(bg="blue",fg="white")
        else:
            self.scaleValue.set(self.Arm.curLeftPos[self.curMoveJoint.get()])
            self.leftPosLabel[self.curMoveJoint.get()].config(bg="blue",fg="white")

    def updateMoveCurrent(self, scaleVal=0):
        """ Updates only the current move joint display
        # Control variables used:
            self.curMovejoint = IntVar()
            self.curStepNumStr = StringVar()
            self.currentArm = IntVar() # right or left
            self.scaleValue = IntVar()
                self.jointTaughtPosVar[n]   #StringVar containing the current (move)
joint (num = n) positions
        # Global variables used:
            curStep
        # Widgets updated:
            self.jointposLabel
        # The currently selected joint and arm
            self.curMoveJoint.set(curJoint)
            self.currentArm.set(curArm)
        # Then the step counter
            self.curStepNumStr.set(str(curStep))
        """
        #print "++++",RobArms.curStep
```

```
                          #print   "update   move   current-",self.currentArm.get(),
self.curMoveJoint.get(),scaleVal
          # Put the actual move command/function (e.g. moveArm(arm = right or left,
curleftPos[] etc.) here
         # Note; moveArm updates the current arm position variables;- curLeftPos and
curRightPos
        # wait until the value of the scale has steadied
        while self.scaleValue.get() != self.prevPosition:
            self.prevPosition = self.scaleValue.get()
        # disable the slider scale widget while the arm is moved
        self.jointmoveScale.config(command=0)
        self.Arm.jointMove(self.currentArm.get(),self.curMoveJoint.get(),scaleVal)
        # Then update the gui display for the current joint selected and position(s)
        if self.currentArm.get() == self.right:
            self.jointCurPosRightVar[self.curMoveJoint.get()].set(self.Arm.curRightP
os[self.curMoveJoint.get()])
        else:
            self.jointCurPosLeftVar[self.curMoveJoint.get()].set(self.Arm.curLeftPos
[self.curMoveJoint.get()])

        if scaleVal != self.scaleValue.get():
            self.updateMoveCurrent(self.scaleValue.get())
        self.jointmoveScale.config(command = self.updateMoveCurrent)

    def updateDisplay(self,keypress=""):
        """ Update all the current move joints displays. needs attention ??? see ???
        # Control variables used:
            self.curMovejoint = IntVar()
            self.curStepNumStr = StringVar()
            self.currentArm = IntVar()    # right or left
            self.scaleValue = IntVar()
                self.jointTaughtPosVar[n]   #StringVar: current  (move)joint(num = n)
positions
        # Global variables used:
            curJoint
            curArm
            curStep
        # Widgets updated:
            self.jointposLabel[n]
        """
        #global curRightPos, curLeftPos, right, left, curStep, numJoints, StepList
        #print "curStep - updateDisplay",curStep, maxStep
        #print StepList[curStep][left]
        #print StepList[curStep][right]
        for n in range(0,numJoints+1):
            self.jointCurPosRightVar[n].set(str(self.Arm.curRightPos[n]))
            self.jointCurPosLeftVar[n].set(str(self.Arm.curLeftPos[n]))
            self.jointTaughtPosVar[n].set(str(self.Arm.StepList[self.Arm.curStep]
                    [self.left][n])+ "    "+str(self.Arm.StepList[self.Arm.curStep]
                    [self.right][n]))
        self.jointSelect()
        self.curStepNumStr.set(str(self.Arm.curStep))
        #self.updateMoveCurrent()
        self.jointmoveScale.focus_force()



# Now first create the RobotArm object, which includes all the data and methods to
# learn and execute a gesture.
# Will automatically connect to the given serial port(default unit 0 = "com1" or
"/dev/ser0").
# Port address may be an integer (0, 1 2 etc) or an actual path or device name
# (e.g.  "com1" or "/dev/ser0" etc.). Use a number to make code both Linux and Dos
# compatible
arm=RobotArm(portAddress)

# Then create the Teach GUI and run it
TkApp = TkTeachArm(arm)
TkApp.mainloop()

# When exiting, Close the serial port properly
```

```
# Could probably do this automatically when program finishes??
arm.ArmComm.flushOutput()
arm.ArmComm.close()

# Finally, a friendly message!
print
print "End of Program"
```

Appendix III: Hardware: The Humanoid Robot head

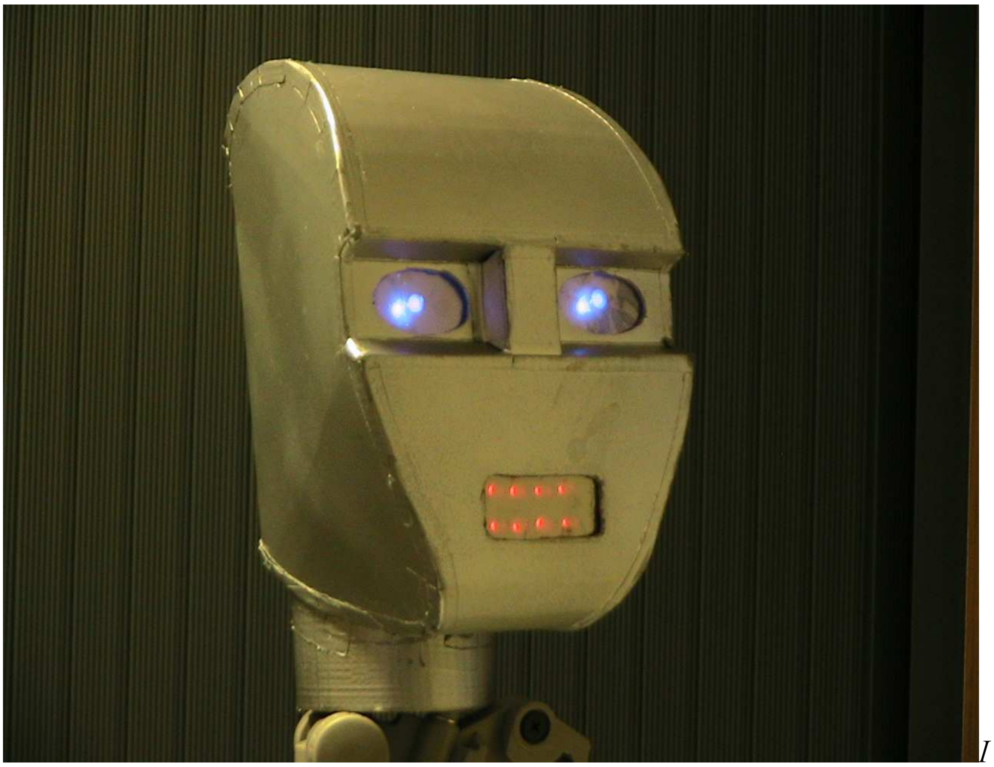
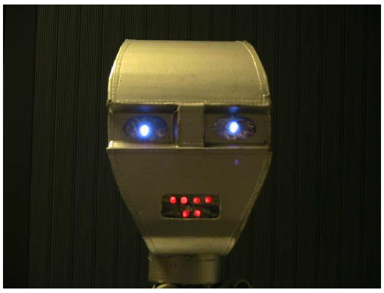


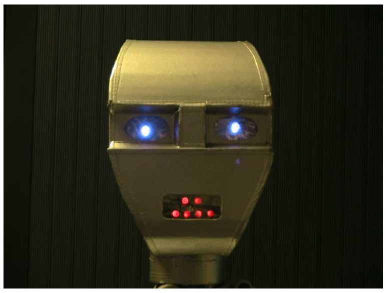
Illustration 7: The Humanoid robot head showing the basic face, "mouth open" with eyes forward.

The Humanoid robot head was made from two A3 sheets of thick cardboard, cut to shape then glued and taped together (cf Chapter 5). The design was specified as being for a robot head which was obviously not realistically human-like, but should possess basic human-like features. LEDS were incorporated in place of eyes and mouth as I thought that the may be used to create simple signals which may aid the user interaction. At present the LEDs are switched for the required pattern by manually remotely operated switches. In the near future, it is planned that the LEDs will be controlled by a dedicated micro-controller which will generate the various expression patterns, and integrated into the robot system by means of a serial link. The pictures below illustrate the design details, how the signalling LEDs operate and how they can be used to provide information to users.

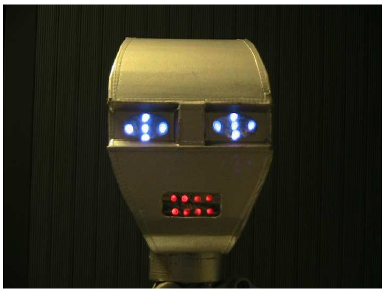
a) All off



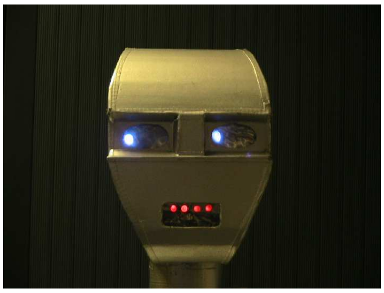
b) "Happy"



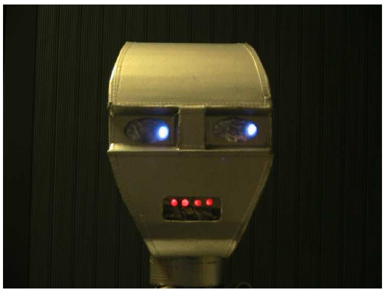
d) "Angry"



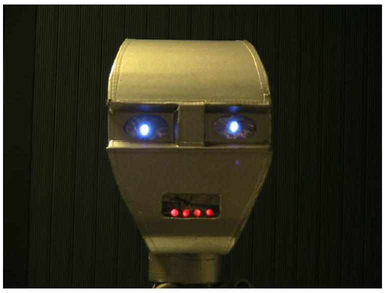
e) "Excited"



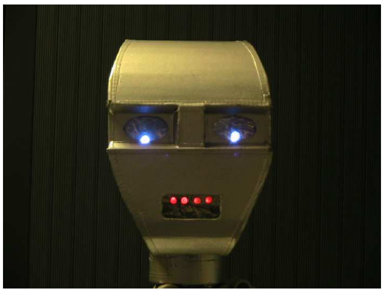
f) Looking left



g) Looking right



h) Eyes forward



i) looking down

j) "Worried"

Figure 7. Illustration 8: Examples of "expressions" that can be shown by switching on different patterns of LEDs in the eyes and mouth of the humanoid head.

Appendix IV: Published Papers from the Study

This appendix contains a list of papers where I am the first author and which are relevant to this thesis:

M. L. Walters, S. N. Woods, K. L. Koay, K. Dautenhahn (2005). Practical and Methodological Challenges in Designing and Conducting Human-Robot Interaction Studies. In *Proceedings of the AISB'05 Symposium on Robot Companions Hard Problems and Open Challenges in Human-Robot Interaction*, UK. pp. 110-119

M. L. Walters, K. Dautenhahn, K. L. Koay, C. Kaouri, R. te Boekhorst, C. L. Nehaniv, I. Werry, D. Lee (2005). Close Encounters: Spatial Distances Between People and a Robot of Mechanistic Appearance. In *Proceedings of IEEE-RAS International Conference on Humanoid Robots (Humanoids2005)*, Tsukuba, Japan. pp. 450-455

M. L. Walters, K. Dautenhahn, R. te Boekhorst, K. L. Koay, C. Kaouri, S. N. Woods, C. L. Nehaniv, D. Lee, I. Werry (2005). The Influence of Subjects' Personality Traits on Personal Spatial Zones in a Human-Robot Interaction Experiment. In *Proceedings of the 14th IEEE International Workshop on Robot and Human Interactive Communication (RoMan05)*, Nashville, USA. pp. 347-352

M. L. Walters, K. Dautenhahn, S. N. Woods, K. L. Koay, R. te Boekhorst, D. Lee (2006). Exploratory Studies on Social Spaces between Humans and a Mechanical-looking Robot. *Journal of Connection Science, Special Issue on Android Science*, *18*. pp. 429-442

M. L. Walters, K. L. Koay, S. N. Woods, D. S. Syrdal, K. Dautenhahn (2007). Robot to Human Approaches: Comfortable Distances and Preferences. In *Proceedings of the AAAI Spring Symposium on Multidisciplinary Collaboration for Socially Assistive Robotics, (AAAI SS07-2007)*, Stanford University, Palo Alto, CA, USA.

M. L. Walters, K. Dautenhahn, S. N. Woods, K. L. K. L. Koay (2007). Robotic Etiquette: Results from User Studies Involving a Fetch and Carry Task. In *Proceedings of the 2nd ACM SIGCHI/SIGART Conference on Human-Robot Interaction (HRI 07)*, Washington DC, USA. pp. 317-324

M. L. Walters, K. L. Koay, D. S. Syrdal, K. Dautenhahn (2007). Longitudinal HRI Trials Video Clips. In *C. Bartneck & T Kanda (Eds) HRI Caught on Film, Proceedings of the 2nd ACM SIGCHI/SIGART Conference on Human-Robot Interaction (HRI 07)*, Washington DC, USA. pp. 177-184

M. L. Walters, K. Dautenhahn, R. te Boekhorst, K. L. Koay (2007). Exploring the Design Space of Robot Appearance and Behaviour in an Attention-Seeking 'Living Room' Scenario for a Robot Companion. In *Proceedings of IEEE-Artificial Life (ALIFE 07)*, Honolulu, Hawaii, USA. pp. 341-347

M. L. Walters, D. S. Syrdal, K. Dautenhahn, R. te Boekhorst, K. L. Koay (2008). Avoiding the Uncanny Valley – Robot Appearance, Personality and Consistency of Behaviour in an Attention-Seeking Home Scenario for a Robot Companion. *Journal of Autonomous Robots 24(2), pp. 159-178*

M. L. Walters, K. L. Koay, K. Dautenhahn, R. te Boekhorst, D. S. Syrdal (2008). Human Approach Distances to a Mechanical-Looking Robot with Different Robot Voice Styles. *Draft, in preparation for publication.*

M. L. Walters, K. L. Koay, K. Dautenhahn, R. te Boekhorst, D. S. Syrdal (2008). Human Preferences and Perceptions of Robot Appearances. *Draft, in preparation for publication.*