How Should a Robot Approach a Pair of People?

Adrian Keith Ball

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Australian Centre for Field Robotics
School of Aerospace, Mechanical and Mechatronic Engineering
Faculty of Engineering and Information Technologies
The University of Sydney

Submitted August 2016; revised October 2017
Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the University or other institute of higher learning, except where due acknowledgement has been made in the text.

Adrian Keith Ball

22 October 2017
Abstract

This thesis experimentally investigates the comfort of pairs of seated people when they are approached by a robot from different directions. While the effect of robot approach direction on the comfort of a lone person has been investigated previously, the extension to a robot approaching pairs of people has not been explored rigorously.

Three maximally-different seating configurations of paired people and eight different robot approach directions were considered. The experiment was augmented with a fourth seating configuration of a lone individual, allowing the responses of grouped and lone participants to be compared. Data obtained from the experiment were analysed using both linear and directional statistics.

Results from 180 unique participants showed that the comfort of a person when a robot approached is influenced by the presence and location of a second person. Analysis of these data with directional statistics showed that participant comfort preference clusters into angular regions of ‘suitable for robot approach’ and ‘unsuitable for robot approach’. This finding shows the importance of avoiding robot approach directions of low comfort, rather than selecting a singular robot approach direction of high comfort. Rayleigh’s test of uniformity, a directional statistics method, also shows across all participant configurations that robot approach directions that minimise participant discomfort align spatially with regions that allow for good line of sight of the robot by both people, and are centred on the largest open space that a robot could approach the group from.

Participants who were grouped also regarded the robot as having more social agency than did lone experimental participants. Grouped participants were less frustrated with the experimental task and also found it less physically and temporally demanding in comparison to lone experimental participants.
Acknowledgements

Firstly, I would like to thank my supervisors, David Rye and Mari Velonaki, for their discussions, guidance and support over the past four years. I would also like to thank David Silvera-Tawil for his thoughtful insight and grounding of my often aloof ideas.

To everyone that I have encountered at ACFR, thank you for providing a warm atmosphere. Thank you for the friendships that have developed and the company on this interesting journey. To those I met at the CRL, thank you for the interesting discussions and the exposure to new and different ideas for the duration of my brief stint in the lab.

I would like to thank Natasha for her support in my endeavours and perseverance with me as I chased my goals. Finally, I want to extend my thanks to my parents for their support and assistance in all my pursuits.
## Contents

Declaration .......................................................... i

Abstract ............................................................ ii

Acknowledgements ......................................................... iii

Contents .............................................................. iv

List of Figures ........................................................ viii

List of Tables ........................................................... x

Nomenclature .......................................................... xii

1 Introduction ............................................................. 1
   1.1 Thesis Contributions ................................................. 4
   1.2 Thesis Structure ..................................................... 5

2 Literature Review ...................................................... 7
   2.1 Human-Human Interaction ............................................. 8
   2.2 Robots Approaching Individuals ..................................... 9
      2.2.1 Modelling Human Preference .................................... 9
      2.2.2 Application of Models .......................................... 12
   2.3 Robots Approaching Stationary Groups ............................. 14
   2.4 Summary .......................................................... 17
3 Experiment Design

3.1 Group Size ......................................................... 20
3.2 Group Configuration .............................................. 21
3.3 Group Activity .................................................... 22
3.4 Experiment Space ................................................. 23
3.5 Robot Design ....................................................... 24
3.6 Robot Approach .................................................... 26
3.7 Wizard of Oz ....................................................... 29
3.8 Experiment Conduct ............................................... 31
3.9 Measurements ...................................................... 32

4 Statistical Theory ................................................... 34

4.1 Parametric vs Non-Parametric Statistics ......................... 34
4.2 Linear vs Directional Statistics .................................. 35
4.3 Linear Statistics ................................................... 35
4.3.1 Mann-Whitney U Test ......................................... 35
4.3.2 Kruskal-Wallis ANOVA ....................................... 37
4.4 Directional Statistics .............................................. 38
4.4.1 Rayleigh Test of Uniformity .................................. 39
4.4.2 Watson’s $U^2$ Test ............................................ 41
4.5 Application of Theory ............................................. 45
4.5.1 Number of Participants ....................................... 45
4.5.2 Data Preprocessing ............................................. 47
4.5.3 Post-hoc Correction Factor ................................. 48

5 Experimental Results ................................................. 50

5.1 Participant Demographics ......................................... 50
5.2 Participant Perception of the Robot .............................. 53
5.3 Task Loading ....................................................... 54
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>Randomisation of Robot Approach Directions</td>
<td>55</td>
</tr>
<tr>
<td>5.5</td>
<td>Inter-position Comparison</td>
<td>56</td>
</tr>
<tr>
<td>5.6</td>
<td>Configuration O</td>
<td>56</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Intra-position Comparison</td>
<td>56</td>
</tr>
<tr>
<td>5.6.2</td>
<td>Inter-position Comparison</td>
<td>57</td>
</tr>
<tr>
<td>5.6.3</td>
<td>Combining the Seating Positions</td>
<td>59</td>
</tr>
<tr>
<td>5.6.4</td>
<td>Configuration O Summary</td>
<td>60</td>
</tr>
<tr>
<td>5.7</td>
<td>Configuration L</td>
<td>64</td>
</tr>
<tr>
<td>5.7.1</td>
<td>Intra-position Comparison</td>
<td>64</td>
</tr>
<tr>
<td>5.7.2</td>
<td>Inter-position Comparison</td>
<td>64</td>
</tr>
<tr>
<td>5.7.3</td>
<td>Configuration L Summary</td>
<td>65</td>
</tr>
<tr>
<td>5.8</td>
<td>Configuration A</td>
<td>66</td>
</tr>
<tr>
<td>5.8.1</td>
<td>Intra-position Comparison</td>
<td>66</td>
</tr>
<tr>
<td>5.8.2</td>
<td>Inter-position Comparison</td>
<td>66</td>
</tr>
<tr>
<td>5.8.3</td>
<td>Configuration A Summary</td>
<td>69</td>
</tr>
<tr>
<td>5.9</td>
<td>Configuration S</td>
<td>70</td>
</tr>
<tr>
<td>5.9.1</td>
<td>Intra-position Comparison</td>
<td>70</td>
</tr>
<tr>
<td>5.9.2</td>
<td>Inter-position Comparison</td>
<td>71</td>
</tr>
<tr>
<td>5.9.3</td>
<td>Configuration S Summary</td>
<td>72</td>
</tr>
<tr>
<td>5.10</td>
<td>Configuration A-CW</td>
<td>74</td>
</tr>
<tr>
<td>5.10.1</td>
<td>Intra-position Comparison</td>
<td>74</td>
</tr>
<tr>
<td>5.10.2</td>
<td>Inter-position Comparison</td>
<td>77</td>
</tr>
<tr>
<td>5.10.3</td>
<td>Configuration A-CW Summary</td>
<td>77</td>
</tr>
<tr>
<td>5.11</td>
<td>Rayleigh Uniformity Test</td>
<td>80</td>
</tr>
<tr>
<td>5.11.1</td>
<td>Configuration O</td>
<td>82</td>
</tr>
<tr>
<td>5.11.2</td>
<td>Configuration L</td>
<td>83</td>
</tr>
<tr>
<td>5.11.3</td>
<td>Configuration A</td>
<td>85</td>
</tr>
<tr>
<td>5.11.4</td>
<td>Configuration S</td>
<td>87</td>
</tr>
<tr>
<td>5.12</td>
<td>Discussion</td>
<td>90</td>
</tr>
</tbody>
</table>
# Contents

6 Conclusion

6.1 Summary ......................................................... 95
6.2 Contributions ..................................................... 97
6.3 Future Work ....................................................... 98

List of References .............................. 100

A Ethics Forms .................................................. 110

B Questionnaires ................................................. 116

C Randomisation of Robot Approach ........ 124
List of Figures

3.1 The four seating configurations used in this experiment. .......................... 22
3.2 Image of the three-dimensional jigsaw in progress. ................................. 23
3.3 Experiment space with the four different participant seating configurations. ................................................................. 24
3.4 The robot used for the experiment is based on a Adept Pioneer 3 DX motion platform fitted with a laptop computer (on motion platform), an Asus Xtion Pro Live RGB-D sensor and a small speaker (upper right). 26
3.5 Configuration L shown with the eight robot approach directions. ............ 27
3.6 Configurations L and A with the robot present. .................................... 28

5.1 Graph of participant birthplace, grouped by geographical region. .............. 52
5.2 Direction labels for data rotated for inter-positional analysis. ................. 56
5.3 The linear distributions of comfort ranks for each robot approach direction for the Individual O data set. ................................................................. 62
5.4 Directional distribution of Rank 8 for the Individual O data set. .............. 63
5.5 Mean angle of the Rank 2 and 8 circular distributions relative to the seating positions for the individual data of Configuration O. ................. 83
5.6 Circular rank distributions for Rank 1 of the Individual O data set and Rank 4 of the group data for Configuration O. ................................. 84
5.7 The mean angles of the three statistically non-uniform rank distributions of the left seating position of Configuration L. ................................. 85
5.8 Circular rank distributions for Rank 1 and 8 of the left seating position for Configuration L. ................................................................. 86
5.9 Circular rank distributions for Rank 2 and 3 of the group data for Configuration L. ................................................................. 86
5.10 The mean angles of the six statistically non-uniform rank distributions of the right seating position of Configuration A. ......................... 88
5.11 Circular rank distributions for Rank 1 and 8 of the right seating position for Configuration A. ...................................................... 88
5.12 Circular rank distributions for Rank 1 and 8 of the left seating position for Configuration A. ....................................................... 89
5.13 The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A. ................................. 90
5.14 Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. ................................................................. 90
5.15 The mean angles of the six statistically non-uniform rank distributions of Configuration S. ......................................................... 91
5.16 Circular rank distributions for Rank 1 and 8 of Configuration S. .... 91
List of Tables

5.1 Level of completed education for all participants. .......................... 52
5.2 Results from the NASA-TLX questionnaire. ................................. 55
5.3 The $p$-values results from a post-hoc multiple pairwise comparison test
   for the top seating position of Configuration O. .............................. 57
5.4 The $p$-values from the intra-position directional analysis of comfort
   rank distributions for Configuration O ............................................ 58
5.5 The $p$-values from the inter-position analyses of the two seating posi-
   tions of Configuration O. .......................................................... 59
5.6 The $p$-values from a post-hoc multiple pairwise comparison tests on the
   Individual O dataset. ............................................................. 61
5.7 Resulting $p$-values from the inter-position analyses of the two seating
   positions of Configuration L. ....................................................... 65
5.8 The $p$-value results from a post-hoc multiple pairwise comparison tests
   on the Group A and Individual AR data sets. ................................... 67
5.9 The $p$-values resulting from an intra-position directional analysis of
   comfort rank distributions for Configuration A. ................................. 68
5.10 Resulting $p$-values from the inter-position analyses of the two seating
   positions of Configuration A. ...................................................... 69
5.11 Resulting $p$-values from post-hoc multiple comparison tests for Config-
   uration S. .............................................................................. 71
5.12 The inter-positional $p$-values obtained by comparing Configuration S
   distributions against the equivalent distributions of the individual seat-
   ing positions in the other configurations. ........................................ 73
5.13 Resulting $p$-values from intra-positional post-hoc multiple comparison
   tests for Configuration A-CW. ..................................................... 75
5.14 Resulting \( p \)-values from directional intra-positional \textit{post-hoc} multiple comparison tests for Configuration A-CW. \hspace{1cm} 76

5.15 Linear inter-comparison \( p \)-value results of Configuration A and Configuration A-CW. \hspace{1cm} 78

5.16 Directional inter-comparison \( p \)-value results of Configuration A and Configuration A-CW. \hspace{1cm} 79

5.17 Results of the Rayleigh test for uniformity and the mean angles for all ranks in all group and individual seating positions. \hspace{1cm} 81

C.1 Chi-squared results for a Kruskal-Wallis ANOVA test on the ordinal comfort-rank distributions for the seven different seating locations. \hspace{1cm} 125
Nomenclature

List of Symbols

\( H_0 \)  
Null hypothesis

\( H_a \)  
Alternate hypothesis

\( R \)  
Vector sample mean for the Rayleigh Test of Uniformity

\( S \)  
Sine component of \( R \)

\( C \)  
Cosine component of \( R \)

\( U \)  
Mann-Whitney \( U \) statistic

\( U^2 \)  
Watson's \( U^2 \) statistic

\( \alpha \)  
Statistical significance level

\( \theta \)  
Angular variable of robot approach directions

\( \chi^2_{\text{dim}} \)  
Chi-squared distribution of dimensionality \( \text{dim} \)

List of Acronyms

ANOVA  
Analysis of variance

FDR  
False discovery rate

FWER  
Family-wise error rate

KW-ANOVA  
Kruskal-Wallis one way analysis of variance

RGB-D  
Red, green, blue - depth

TLX  
Task load index

WoZ  
Wizard of Oz
Chapter 1

Introduction

The design and development of robots to interact with people has lead to an increasing presence of robots in social spaces (Christensen and Pacchierotti, 2005); spaces that people occupy and interact with each other in. This is a break from ‘tradition’, where robots were usually developed for industry and/or the automation of tasks, such as packing boxes. In the ‘traditional’ deployment of robots, the space in which they operate is often heavily engineered, with access by people restricted or prohibited for reasons of safety and task efficiency. Introducing robots into social spaces to interact with people provides researchers with new challenges; environments are dynamic and not designed specifically and solely for robot operation, and robot operation with and around people introduces further complexities that need to be considered.

If robots are to interact with or around people, then behaviours and actions of people need to be understood, meaning that the robot needs to have some level of social awareness (Riek and Howard, 2014). At the same time though, people need to be able to understand the robot. This means that robots in social environments must act in ways that are intelligible to people. As humans are social creatures that apply social models to understand scenarios (Reeves and Nass, 1996), the actions of robots in social spaces have to align with the social models that people have. This is required to ensure that robot actions can be understood.
To make the actions of a robot in a social space understandable often means that the robot needs to have a model of a scenario that aligns with that of the people in the scenario. While modifying the robot action, such as, the incorporation of forethought (Takayama et al., 2011), can help, the robot still needs to perform the appropriate action at the appropriate time. For example, robotic receptionists (Gockley et al., 2005; Lee et al., 2010) should understand when people wish to interact with it and when people are passing by the robot en route to another location. This means that robots need to have a model of the social space that is consistent with the model that people have of the space. For robots that approach people, such as to assist customers in shopping centres (Gross et al., 2009; Kanda et al., 2009), parameters such as robot speed, distance to goal location and orientation relative to the person (Carton et al., 2013) need to be considered. It is important to understand how changing these parameters influence the comfort of a person. This means that an understanding of how people socially model and understand space is required. Examples include how people use space when interacting (Hall, 1966), the angle of a robot’s approach into an interaction with a person (Dautenhahn et al., 2006) and whether the robot is approaching one or more people (Ball et al., 2015a).

The initiation phase of an interaction is important for the success of the interaction (Mead et al., 2013). An important aspect of the initiation phase is the direction of approach one social agent takes relative to another. This idea has been explored in the literature with a robot approaching individuals (Walters et al., 2007; Torta et al., 2011; Avrunin and Simmons, 2013), with results demonstrating that people are generally most comfortable when the robot approaches from a ‘frontal’ direction. However, given the social nature of humans, it is of interest to understand how a robot might approach a group of people who are already interacting with each other.

When people interact with each other, they orient themselves such that the transactional space of each person overlaps, forming a shared transactional space (Kendon, 1990). This requires a robot to adopt a different strategy when approaching a group of people compared to the strategy used to approach an individual. A motivating example is a scenario where a robot needs to approach a pair of people who are facing
Introduction

each other. If the robot was to approach one person from a ‘frontal’ region to ensure their comfort, then the robot would be approaching the other person from a ‘rear’ direction, a direction that is relatively less comfortable for the second person. Beyond this, the thoughts and behaviours of people also change from when they are alone to when they are in a group (Hare, 1976). This makes the comparison of personal comfort when a robot approaches for individuals and grouped people an interesting research task.

Towards understanding which approach direction a robot should take towards a pair of people, answers were sought to the following questions:

• Which approach directions are most and least comfortable for a robot to take towards a pair of people?

• Can a comfort map or profile be defined for a group?

• Does the relative orientation of the two people influence their comfort when the robot approaches?

• How does the comfort of an individual compare to that of a grouped person when a robot approaches?

This thesis presents the design, execution and results of an extended experiment with the objective of answering the above questions. Briefly, the experiment involves a robot approaching pairs of people from several discrete directions. Different relative configurations of the participants are used, and a scenario with a lone individual is included to provide a comparison between the responses of grouped and lone people. The data are analysed using linear and directional statistical methods. These methods allow for a comparison of data within and across the different seating positions.
1.1 Thesis Contributions

This thesis explores the comfort responses of pairs of seated people when they are approached by a robot from eight discrete directions through the conduct of an experiment. The principle contributions of the thesis are:

- Performance of an experiment to assess the comfort of paired participants when a robot approaches from different directions. The experiment was performed over three different seating configurations, each with a sufficiently large sample size for the results to have high power.

- Statistical evaluation of the experimental data, allowing for the presentation of comfort models for pairs of people in three different seating configurations. The comfort models for each seating configuration are shown to be different. The direction of robot approach that is most comfortable when considering both seating positions is also presented for each seating configuration.

- Extension of the experiment to include the scenario of a lone participant approached by a robot from different directions. Results from statistical analysis of the data from this scenario were similar to previously published experiments. This provides a measure of validity in terms of experiment design, but also allows for a comparison of results across different cultures.

- Statistical comparison of paired and lone participant responses to an in-experiment and post-experimental questionnaire. The comparison of comfort data demonstrates that the presence and location of a second person influences the comfort profile of the first. Comparison of non-comfort data shows a change in participant perception of the robot that approached them during the experiment.

- The use of directional statistics to demonstrate that when people have a comfort preference for the robot approach direction, the preference coarsely clusters into two general regions of ‘suitable to approach from’ and ‘unsuitable to approach from’.
1.2 Thesis Structure

The remainder of the thesis is structured as follows:

**Chapter 2** reviews literature related to developing a personal comfort model for an individual who is approached by a robot. These works include the comfort of a person when they were approached by a robot, the influence of someone’s personality on their comfort when they were approached by a robot, and an analysis of interaction distances when robots approach people and when people approached robots. A brief overview of social robot navigation is also provided for motivation on why models of people are important and how these models fit into the larger field of social robotics. Finally, models of groups of people are explored along with literature on the implementation of a robot approaching groups of people.

**Chapter 3** defines experimental objectives and introduces the experiment conducted for this thesis. Several design choices were required, such as group size, size and shape of the robot, and the task for participants to work on for the duration of the experiment. These choices are explored and brought together to present an experiment for understanding the comfort of pairs of people when approached by a robot.

**Chapter 4** presents the statistical theory used for the analysis of experimental data. The concept of linear and directional statistical methods are introduced at a high level and the differences between the two domains of statistical methods are explained. Following this, the specific statistical methods used for data analysis in this thesis are presented. Some of the statistical methods have application-specific parameters that need to be set. These parametric values are set by relating the statistical methods to the experiment.
Chapter 5 presents the experimental results. This includes the data that were obtained through the experimentation process along with the results of the statistical analyses defined in Chapter 4. Non-comfort data such as participant demographics and participant perception of both the robot and the in-experiment task are presented, followed by an analysis of the comfort data. Analysis of participant comfort data in, and across, the various seating configurations, including the configuration of a lone individual are presented. The presentation of these results are grouped by seating configuration, allowing for a comfort model for each different seating configuration to be presented.

Chapter 6 concludes the thesis and discusses areas of future research.
Chapter 2

Literature Review

This chapter reviews literature on the comfort of individual people when they are approached by a robot, and how models are applied to robot path planning in a social environment. This thesis uses a natural language understanding of comfort; tranquil enjoyment and contentedness, freedom from unease, anxiety and fear. This notion of comfort is consistent with all cited works. A brief background on the more general field of robot navigation in social environments is provided to add motivating context to this particular area of research. Finally, the literature on models of human groups when approached by a robot is reviewed.

When a robot approaches a person, or group of people, to initiate an interaction it is important to consider how the approach of the robot is made. The approach of a robot forms part of the initiation phase into an interaction with a person or group of people. This phase is important to the success of the interaction (Mead et al., 2013), since a poor initiation phase could lead to an unsuccessful or uncomfortable interaction. The approach of the robot to the target person or persons also has to be distinct so that the intent of the robot is understood (Lichtenthäler and Kirsch, 2016). It is therefore important to have an understanding of what people find acceptable and comfortable when a robot approaches them.
2.1 Human-Human Interaction

Such research lies in the field of proxemics; the “study of man’s interpretation, manipulation and social use of space” (Hall, 1966). While social signals such as speech and gesture are important proxemic features that need to be considered by a robot that interacts with people (Rios-Martinez et al., 2015), this thesis explores how the comfort of a person in a group is affected by robot approaches from different directions, and by the presence of another person.

2.1 Human-Human Interaction

The work of Reeves and Nass (1996) showed that humans are social creatures as they anthropomorphise objects and apply social models to understand a situation. A classical example is presented in the work of Heider and Simmel (1944) where a short film of two triangles and a disc were shown moving about a rectangle. While these are only shapes on a screen, experimental participants readily assigned personalities to the shapes and a story to their movement. If researchers can understand the social models that humans apply to the world when interacting with it then it may be possible to design social robots that are more socially intuitive.

Hall (1966) identified four spatial regions that people may occupy as they interact with each other. The regions and their spatial extents, as defined by Hall, are labelled the “intimate” (0–0.46m), “personal” (0.46–1.2m), “social” (1.2–3.7m) and “public” (3.7–7.6m) regions. The region that people choose to stand in when interacting with each other is influenced by the closeness of the relationship between the interactants.

Work by Kendon (1990) introduced F-formations for providing structure when recognising groups of people. The F-formations—or facing formations (McDermott and Roth, 1978)—arise when two or more people orient themselves such that they have overlapping transactional spaces. There are three spatial regions defined in the F-formation: ‘o-space’, ‘p-space’ and ‘r-space’. The o-space is the transactional space shared by all members of the interaction and is maintained for the duration of the interaction. The o-space is the central space of the interaction and is surrounded by the p-space. The p-space is the region that an agent must occupy to be considered
part of the interaction. The r-space is the nearby space surrounding the p-space. The r-space is a region monitored by group interactants and is a space a person might occupy before joining the group.

2.2 Robots Approaching Individuals

2.2.1 Modelling Human Preference

The work of Hall has been repeated in similar scenarios but with a person interacting with a robot. Results showed that people placed themselves at a distance from the robot such that they would be in the personal or social region if the robot were a person (Walters et al., 2005; Hüttenrauch et al., 2006; Cass et al., 2015; Silvera-Tawil et al., 2015). If the previous scenario is reversed such that the robot approaches the person, people are more comfortable when the robot stops approaching at a distance that lies in either the personal or the social region (Walters et al., 2006). If the robot approaches too close, such that the person becomes uncomfortable then the person will reposition themselves at a more comfortable distance that is further away from the robot (Sardar et al., 2012). These results were also verified in an independent study by Takayama and Pantofaru (2009).

An experimental study was performed by Dautenhahn et al. (2006) where a robot approached a seated person after fetching a requested object. The experiment was performed with 38 participants recruited from a conference. A follow-up trial was also performed with 15 participants to validate the results of the initial experiment. In the experiment the robot approached from either a front–left, front–right or a direct frontal position. It was found that the front–left and front–right approach positions were the most comfortable for participants. The direct frontal approach was considered to be “uncomfortable” and in some cases “confrontational”, but only in comparison to the other frontal approach directions, as alternate robot approach directions were not considered.
The above experiment was extended by the work of Walters et al. (2007) by including four additional scenarios. A total of 42 persons participated in this follow-up experiment. These participants were recruited from the University of Hertfordshire. Participants were either standing against a wall, standing in the middle of a room, seated in the middle of a room or seated at a table in the middle of a room. Participant preferences for the robot approach directions were found to be consistent across the different scenarios and also consistent with the earlier experiment of Dautenhahn et al. (2006). The work of Walters et al. (2007) also included situations where the robot approached participants from behind. These robot approaches were rated the least comfortable, along with cases where the robot approached from directly in front of the participants. Only four directions of robot approach were evaluated in the experiment by Walters et al. (2007), providing scope for a more detailed analysis.

In conjunction with the experiment performed by Walters et al. (2007), work by Syrdal et al. (2006) explored the idea that people with different personalities would have different comfort preferences when approached by a robot. The Big Five personality model (Tupes and Christal, 1992) was used to parameterise participant personality. Results from a non-parametric Friedman analysis (Sheskin, 2003) showed that while the personality traits of individuals did not have an influence on the comfort preference for directions of robot approach, participants with higher extraversion scores had a higher tolerance to the less comfortable directions of robot approach.

Avrunin and Simmons (2013) conducted an analogous experiment where participants approached an experimenter to pass an object. The experimenter was approached from either the front, back or right side while looking to the left, right or front. The experimenter was not approached from the left side due to the author’s belief that approaches from the left were analogous to approaches from the experimenter’s right side. A total of seven people who were recruited on Carnegie Mellon University campus took part in the experiment. The path taken by the participants was recorded for each approach, with the intent of reproducing similar paths for when a robot approaches a person. Results showed that participants preferred to approach so that they were in the field of view of the experimenter being approached. While this
work is introductory, no statistical analysis was presented in determining the required number of participants for the experiment. Given that only seven people participated in the experiment, it is likely that the results have low statistical power. The authors asserted that a reward function could be developed from the obtained data but no specifics were provided.

The idea of curved versus straight robot approach paths was investigated by Shomin et al. (2014). An experiment was performed where a robot approached a participant along a straight or curved path. The experiment had 15 participants, all of whom were recruited through online postings on a university campus. Results of their experiment showed that participants preferred the straight robot approach paths to the curved ones but found both comfortable. A weakness of the experiment is that it does not define the curvature of the robot’s path, claiming only that robot approaches along the curved path were further from the participant. Also, no robot approach strategy was proposed such as the one suggested in the work of Avrunin and Simmons (2013) where the robot should take a path that maximises its time in the field of view of the person being approached.

Torta et al. (2011) presented a navigation architecture that allows a robot to avoid obstacles and approach a person from a frontal direction. A crescent-shaped contour graph was generated in front of the person being approached, with more weighting given to the region directly in front of the person. This graph was generated by having a robot approach a seated person who pushed a button to signify distances that were the closest, furthest and optimal for comfortable communication with the robot. A total of 10 participants were used in the experiment. The authors demonstrated that a robot is able to avoid objects while approaching this crescent-shaped region around the person. The personal space model presented in this work was suitable for the Aldebaran NAO robot, the robot used in the work of Torta et al. (2011). However, the NAO has minimal physical presence on a human scale so the validity of the model needs to be tested with other robots. Furthermore, approaches from the person’s side or behind were not considered.
2.2 Robots Approaching Individuals

A reinforcement learning model of a robot approaching people was presented by Macharet et al. (2013). The presented example was a simulation where a robot approached people to hand out flyers. Each robot approach to a person was considered successful if the person took a flyer. This model is of interest as it demonstrates the ability of a robot to learn algorithmically how it should approach a person based on the reward function of a learning model. A disadvantage of using a reinforcement learning model in practice is that the robot must inevitably perform suboptimal approaches towards a person which may in turn provide a negative interaction experience. However, if an appropriate initial model of how a robot should approach a person or group of people was pre-loaded on a robot, the awkward initial learning phase could be avoided. The reinforcement learning algorithm could then be employed to optimise how a robot should approach a person or group of people over time. The work presented in the present thesis could be used to provide the initial model for a robot approaching one or two people.

2.2.2 Application of Models

The previous section discussed literature that explored human models that can be used in social robot navigation algorithms for approaching a person. A few examples of the application of these algorithms are presented below. Some examples related to the field of social robot navigation are explored to provide context for the application of human comfort models.

Kessler et al. (2011) implemented the model of a person’s comfort preference described in Dautenhahn et al. (2006) as a sum of Gaussians. The Gaussians are defined relative to the location and orientation of the person, allowing for the cost of approach from a frontal region of the person be lower than the cost of an approach from any other direction. The authors then use the direct window approach defined by Thrun et al. (1997) for planning how the robot should approach the person. The direct window approach to the motion planning of a robot can be thought of as a series of small temporal windows where locally optimal decisions are made. A similar sum of Gaussians model was defined by Svenstrup et al. (2009).
Sisbot et al. (2007) implemented a human-aware mobile robot path planner for scenarios where human safety was paramount. A Gaussian distribution was used to define a ‘safety bubble’ about a person and regions identified as being not visible to the person had an increased cost assigned for robot traversal. The path with the lowest cost was then determined using the $A^*$ planning algorithm. If the goal of the robot was to approach the person, the visibility costs forced the robot to approach the person from a frontal zone. This philosophy is in accord with the models explored in Section 2.2.1. Sisbot et al. (2010) explored how the human-aware algorithm could be implemented in a complete human–robot interactive task scenario.

Kanda et al. (2008) demonstrated a robot in a busy shopping centre where it could identify people who might be interested in having a conversation, or being invited into a store. A database of human traffic data was collected over the course of a week and used to identify behaviour patterns in the shopping centre. The robot anticipated people that it deemed appropriate based on the similarity of their location or behaviour to those identified in the database. The robot approached people by moving to their general vicinity and only completed the approach when it was noticed by the target person. This application is interesting as it explores the practical issues of the robot identifying and approaching a suitable person. Kato et al. (2015) extend this work with the development and implementation of an algorithm to better estimate pedestrian intention.

When a particular person needs to be approached, rather than a selected ‘suitable’ person as described above, Tipaldi and Arras (2011) present a spatial affordance map to learn about human spatio-temporal patterns. The spatial affordance map could then be combined with a human comfort model so that the robot could locate and approach a person without causing them discomfort. Diego and Arras (2011) also demonstrate the inverse idea where a robot can learn to avoid people. This is useful for service robots that operate in a social environment but do not need to interact directly with people.
While the previous examples allow for the target person to be moving, the complexities associated with the particular problem of approaching a moving person are explored in more detail by Kanda et al. (2009), Satake et al. (2013), Carton et al. (2013), Kidokoro et al. (2013) and Ikeda et al. (2013). Related problems of robots navigating through crowds are also explored by Trautman et al. (2015) and Vasquez et al. (2014). In the cited studies of robots approaching a pedestrian, the researchers endeavour to have the robot approach the person from a frontal location so that the robot can be observed. This is done for practicality, so that the person does not miss the opportunity for an interaction with the robot. These robot approach paths also align with the more comfortable directions of robot approach (Section 2.2.2).

When groups of people are walking, they orient themselves towards their direction of travel (Ge et al., 2012). The relative orientation of a small group of stationary interacting people is different; stationary groups align themselves such that they have a shared transactional space (Kendon, 1990). A walking group cannot be regarded as an extension or variant of a stationary group. As the focus of this thesis is on how robots should approach a stationary group, literature of robots approaching moving groups is outside the scope of the research and is not presented here. The work of Kruse et al. (2013) is, however, recommended as a starting point for readers interested in a more detailed analysis of the general human-aware robot navigation field. The following section reviews the literature on robots approaching stationary groups of people.

### 2.3 Robots Approaching Stationary Groups

One of the earliest investigations of how robots should approach groups of people was performed by Althaus et al. (2004). They presented a robot behaviour profile to allow a robot to approach a group of people and maintain an f-formation (Kendon, 1990). Parameters of the robot behaviour were based on distance measurements of the group members to the robot. An example behaviour is the robot speed, which was defined as a function of the distance between the robot and group. Althaus et al.
(2004) showed in this early work that the presented behaviour profile generated robot actions that appeared natural to the experimental participants. This early work only used one group of three participants.

Gómez et al. (2013) presented a mathematical formulation for the navigation of a robot in a social space. The work provides a novel mathematical representation of a group and its o-space (Kendon, 1990), allowing the robot to not only avoid individual people, but also to avoid passing through the shared transactional space of a group. The o-space of the group is defined as a Gaussian distribution. Its parameters are determined by calculating the parameters for ordered pairs of people in the group and then averaging the results for a final Gaussian distribution. While the approach of a robot to a group is not explored in depth by the authors, it is conceivable that the mixture of Gaussians formulation could be used as a cost map for a robot approach.

An online survey exploring the perceived comfort of the approach by a robot to a simulated family of three was presented by Joosse et al. (2014). Social psychologists have identified that culture influences proxemic models (Sussman and Rosenfeld, 1982) and the work of Joosse et al. (2014) specifically explored the effect of culture on robot approach distances to groups of people. The simulated group stood in a circular F-formation with a radius of 0.61m. This placed the simulated family members 1.06 metres apart, with each family member in each others personal space. A distance of 0.8 metres from the centre of a group was found to be the most appropriate stopping distance with some deviation based on the cultural background of the surveyee. These distances put the robot in a personal or social zone— as defined by Hall (1966)—relative to the person on the opposite side of the group to the robot approach path.

Introductory work on the comfort of a pair of people when approached by a robot was presented by Karreman et al. (2014). They demonstrated that individuals in the group had comfort results consistent with those of the lone individuals in the works of Dautenhahn et al. (2006) and Walters et al. (2007), with participants finding front-left and front-right directions of robot approach comfortable and robot approaches from behind uncomfortable. While the work of Karreman et al. is similar to the work
presented in this thesis, as a pilot study it had a low volume of experimental data and was therefore unable to demonstrate rigorous statistical analysis. The work of Karreman et al. was extended by Ball et al. (2014, 2015a,b). These extensions were completed during the course of this degree and their content forms part of this thesis.

Vroon et al. (2015) presented a study that explored the position and orientation of a telepresence robot when it was approaching, conversing and retreating from a group of three people. A total of 56 participants were recruited for this experiment. While the work presented is preliminary and a more thorough analysis of the data is required, the results showed that the experiment participant controlling the telepresence robot drove the robot towards the gap between the other participants that was closest to the robot in almost all experiment trials. In the highest-rated robot approaches, the telepresence robot stopped at an average of 1.25 metres from the center of the group. Again, this places the robot at a distance from each group member that lies in personal or social zones as defined by Hall (1966). From the data, the authors hypothesise that a robot should approach people to a distance of 1.25 metres. While this specific hypothesis is yet to be tested, the results cannot be extended directly to an automated (non-teleoperated) robot as knowledge of the use of the Wizard of Oz scenario\(^1\) in human-robot interaction experiments influences both perception and expectation of the robot and its actions Fraser and Gilbert (1991).

Narayanan et al. (2016) demonstrated a robot capable of joining a group of interacting people. When a group of people is identified, sensor data is used to mathematically represent the group’s F-formation. The target location of the robot to join the interaction is then determined as a point in the group’s p-space, and a robot orientation such that it is facing the centre of the group. The authors observe that there are multiple geometric solutions that satisfy this requirement, but do not define if, or how, the problem should be constrained to yield a single solution. While a robot capable of approaching people is demonstrated, comfort preferences of the people being approached are not considered. This in turn means that there is no analysis on the change of group formation when the robot joins, or on the effect that different robot

\(^{1}\)The simulation of an autonomous system by using a hidden person to control the system. See Section 3.7 for a more comprehensive definition.
A robot navigation framework which can account for the social zones of people was demonstrated by Truong and Ngo (2016). The authors use the comfort model of an individual being approached as defined by Dautenhahn et al. (2006) and Walters et al. (2007). The work reported the approach of a robot to a test group consisting of three people in a ‘T’ formation to be comfortable. It is possible that the chosen robot approach path is ‘obvious’ and future work is needed to rigorously test the proposed framework with alternate group formations. Furthermore, the work is conducted with the implicit assumption that people in groups have the same comfort model as individuals. Work published in contribution to this thesis (Ball et al., 2015a) demonstrated that, while strong similarities between the comfort models of people who are alone or in a group exist, differences arise due to the presence and location of the other person. Chapter 5 explores in detail the differences between the comfort of paired and lone people.

2.4 Summary

Research has shown that when humans interact with each other, dynamic spatial arrangements of people known as F-formations are established. One of the factors that influences the distances between people in these formations is the level of intimacy between the interactants. The extension of this to humans interacting with robots has shown that people prefer to interact with social robots when they are in the personal to social range (0.46–3.7m). When robots approach individuals to initiate an interaction with a person, it was demonstrated that not only did people prefer the robot to approach from a point in their field of vision, but such an approach was often required for the interaction subsequently to take place—especially when people were walking. While models have been presented of robots being able successfully to join a group of interacting people, only preliminary work has been performed on investigating how the presence and relative position of other people influence a person’s comfort when a robot approaches. It is here, in the analysis of the comfort of grouped people, that this thesis makes a contribution.
This chapter presented a review of the literature of models of human comfort when people are approached by a robot. A brief review of robot navigation in social environments was also presented to provide context for the need for human comfort models when a robot approaches. Most of the presented literature investigated the comfort of individuals when being approached by a robot, or provided examples of implementations where the comfort of a person is not directly considered. These shortcomings provide motivation for exploring the comfort of groups of people when approached by a robot from different directions. Chapter 3 next presents the objectives and design of the experiment performed for this thesis.
Chapter 3

Experiment Design

This chapter develops the design of an experiment to measure the comfort of grouped participants when a robot approaches. The aims of the experiment are to:

- Measure the comfort of grouped participants when a robot approaches;
- Have participant comfort responses for several robot approach directions;
- Understand how group configuration influences participant responses;
- Compare grouped and lone participant responses in similar situations;
- Quantify the suitability of different robot approach directions based on participant comfort responses;

The specifics of the experiment design to meet the above aims are described in the remainder of this chapter. Ethics approval for the undertaking of this experiment was granted by the Human Research Ethics Committee of The University of Sydney. Ethics forms associated with this experiment can be seen in Appendix A, and the complete participant questionnaire in Appendix B.
3.1 Group Size

Groups have a lower bound of two people for their size and there is no upper bound to the number of people that can be in a group. Free-forming groups have a size that range from two to seven people, with a mean size of 2.3 people (James, 1953, 1951). As groups grow larger than this, they often break down into a collection of sub-groups (Hare, 1976) as the benefit to an individual from participation in a group is often related to their mean participation time (Dunbar et al., 1995). As groups become larger still, to the size of a crowd or mob, they start to have their own behavioural patterns and rules that are different to smaller free-forming groups (Forsyth, 2006).

As one of the aims of this experiment is to understand how the comfort of a person approached by a robot changes from when they are alone compared to when they are in a group, it is desirable for the size of the experimental group to be in the free-forming group range. This is because the smaller groups are the closest in size to that of an individual, which can be thought of as a group of size one. Given the distribution of free-forming group sizes found by James (1953, 1951), an ideal experiment group would consist of two or three participants.

From a practical perspective, it is more feasible to perform experiment trials with groups of two rather than with groups of three. For groups of two people there are three maximally different seating configurations (Section 3.2) while for groups of three people there are five maximally different seating configurations. Performing 20 experiments in each seating configuration (Section 4.5.1) means that 120 participants would be required to test the configurations with groups of two people, and 300 participants would be required to test all configurations with groups of three people. For these pragmatic reasons, the experiment present focussed on groups of two people. Section 6.3 does discuss the results of the experiments and how they might form a hypothesis for future work that extends to groups of more than two people.
3.2 Group Configuration

Kendon’s F-formations (Kendon, 1990) provide a structure for recognising the formation of groups. An F-formation, or ‘facing formation’ (McDermott and Roth, 1978), forms whenever two or more people orient themselves such that they share an overlapping transactional space. For pairs of people, there are three maximally-different configurations; the two people can be opposite each other, in an ‘L-shape’, or side by side. These configurations are used in this experiment and are respectively referred to as Configurations O (“opposite”), L (“L-shaped”) and A (“adjacent”). A fourth configuration with a lone participant labelled “Configuration S” was also defined so that group and lone participant responses could be compared.

While this experiment was underway, it was observed that asymmetric results were obtained for Configuration A (Section 5.8). To investigate this asymmetry, a fourth group configuration was included. This configuration, labelled “Configuration A-CW”, is the same as Configuration A, except that the robot travelled clockwise around the room when viewed from above instead of counter-clockwise. It is hypothesised that the reflection of the experiment trial should give a reflection in the corresponding participant response. The starting location for the robot in these experiment trials was the corner of the experiment space associated with Direction 7 (Figure 3.5). This configuration was chosen to be a reflection about the axis defined by robot approach directions 4 and 8 of original Configuration A.

The participants were seated in low armchairs to ensure that they remained in the prescribed seating configuration for the duration of their experiment trial. Prior to the commencement of each experiment trial the chairs were arranged in an F-formation around a table, which provided the focus of the shared transactional space. The layout of the four configurations can be seen in Figure 3.1.
3.3 Group Activity

It was desired that participants were given a task to work on for the duration of the experiment. Assigning the task was intended to prevent anticipation of the robot’s approach and to distract participants from the position and movements of the robot between successive approaches. By adding this task defined by the experiment to the list of other tasks that participants might engage in, such as monitoring the position and movement of the robot, it is expected that participant performance of monitoring the robot will decrease (Carrier et al., 2015; Adler and Benbunan-Fich, 2012).

There are several characteristics that the ideal task would have. These include:

- Engaging: A non-engaging task would be ignored by the participants, defeating the purpose of the task.

- No turn-taking mechanism: If participants alternate turns on the task, there is a higher chance that participants will be more cognizant of the robot when their input to the task is not required.

- Easy to understand: A task that is easy to understand is more accessible to the general public. If the task is also familiar to participants then less explanation is required before the start of each experiment trial.

- Temporally demanding: The time to complete the task has to be at least as long as the duration of the experiment. This is to ensure that participants would always be distracted from the movements of the robot.
3.4 Experiment Space

- Be accessible to pairs and individuals: As the experiment will be performed with both individuals and pairs of people, it is ideal that the experiment process, including the task, be constant across the different group sizes.

Given these criteria, a three-dimensional jigsaw puzzle was chosen as the task for participants to work on for the duration of the experiment. While the level of participant engagement with the jigsaw puzzle is subjective, the puzzle does meet the rest of the listed criteria. A three-dimensional puzzle was chosen as the third dimension of the jigsaw puzzle increases both the novelty and complexity of the task. To measure participant engagement with the jigsaw puzzle, the NASA Task Load Index (TLX) questionnaire (Hart and Staveland, 1988) was included in the post-experiment questionnaires (Section 3.9). Figure 3.2 shows the jigsaw puzzle used for this experiment in a partially assembled state.

![Image of the three-dimensional jigsaw in progress.](image)

Figure 3.2 – Image of the three-dimensional jigsaw in progress.

3.4 Experiment Space

The experiment space needs to be large enough so that the robot can approach the participants from all directions. The distance from the periphery to the participants for each approach direction also needs to be approximately the same to prevent spatial bias in the results. Multiple easily accessible exits should also be present in the space.
3.5 Robot Design

A single exit could make participants feel uncomfortable with the possibility of having to 'confront' the robot to leave the space (Karreman et al., 2014), introducing a bias into the results. A six metre square space was used for the experiment. Exits were available to the participants on three of the sides. A plan of the experiment space can be seen in Figure 3.3.

3.5 Robot Design

An Adept Pioneer 3 DX was used as the motion platform for the robot. An aluminium frame was mounted onto the motion platform to support additional hardware and to give the robot more physical presence. The height of the motion platform and frame was 1.00 metres and chosen as it was the approximate height of an average person.
seated during the experiment (Hiroi and Ito, 2011) and also suggested that the robot had an equal social status to the participants (Rae et al., 2013).

An Asus Xtion Pro Live RGB-D sensor and a speaker were mounted to the top of the aluminium frame. A laptop computer was also present at the base of the aluminium frame. The robot can be seen in Figure 3.4. The speaker was used to provide an audio prompt to participants during each experiment trial. The RGB-D camera was not used for sensor data in this experiment. The laptop computer provided commands to the speaker, though this functionality could have been integrated into the motion platform of the robot. The RGB-D camera and the laptop computer were mounted to the robot for ‘future-proofing’; the camera providing the possibility for additional sensory input, and the laptop computer providing additional on-board computational power.

The presence of the camera and laptop can add support to the perception of robot autonomy, as both the appearance and behaviour of a robot provide insight towards its capabilities (Goetz et al., 2003). A robot can also be thought of as more than the sum of its parts (Liu and Wu, 2001; Brachman, 2006) in that it has emergent properties resulting from the assembly of its parts. Adding devices for future experiments could change some emergent properties of the robot, such as participant perception. By including these devices now, the appearance of the robot will remain constant across future experiments. It was also intended that the robot be mechanical in appearance to facilitate comparison of results with other research using similar robots.

Participant likeability towards the robot can be improved if the noise generated by the robot is related to functionality of the robot (Lohse et al., 2013; van Berkel, 2013; Joosse et al., 2014). The robot used for this experiment travelled at a constant speed of approximately one metre per second. The noise generated by the motion platform when the robot was moving had constant loudness. It is desirable that participants are not affronted by the robot so that they stay for the complete duration of their experiment trial. The only other time the robot generates noise is when an audio cue is played from the speaker, directing participants during the experiment trials (Section 3.8). Again this sound is used for a functional purpose.
3.6 Robot Approach

There are eight points around the periphery of the experiment space that are easily identifiable. These are the corners of the experiment space and the centre of the sides which can be lined up with the table placed in the centre of the experiment space. These points were chosen to be where the robot would approach the participants from. More robot approach directions would increase the length of the experiment trials which would increase the chance of temporal bias in participant responses and make the experiment trials logistically harder to complete. If a uniform spread of robot approach directions was maintained to ensure symmetry of the robot approach directions relative to all configurations, then the next number of robot approaches required would be sixteen\(^1\), doubling the duration of each experiment trial. The visual identification of the initial locations for the robot to approach each group from is important as the robot was controlled by a ‘Wizard’ (Section 3.7) and not automated. Figure 3.5 shows the eight robot approach directions spaced at 45 degree intervals around the group. Each approach direction was used once for each experiment trial, and the order of robot approaches was random for each trial so that there was no ordinal bias with respect to the robot approach directions.

\(^1\)A new approach from the middle of all current robot approach directions would be added.
A social space can be defined as a relational arrangement of living beings and social goods (Löw, 2008). From this definition the experiment space can be thought of as a social space and if the definition is expanded to include social agents rather than people then the participants and the robot would be the social agents. To increase perception of the robot being a social agent, it is important that the robot is aware of and can follow societal behaviours (Lindner and Eschenbach, 2011; Duffy, 2003). For this reason it is important that when the robot approaches the group it enters or gets as close as possible to the p-space of the group. The p-space (Kendon, 1990) is the region that participants of an interaction occupy while orienting themselves towards the shared transactional space: in this experiment, the table.

If the robot approaches from a direction that coincides with the location of a participant, it will not be able to enter the p-space. If the robot approach direction is at least 90 degrees from any seating position (e.g., Directions 8, 1, and 2 in Figure 3.5), then the robot is sufficiently far from the participants and will be able to enter the p-space of the group. Figure 3.6a shows that when approaching groups from a direction adjacent to a participant, the robot has sufficient space to be able to enter the p-space. This holds for Configurations O, L, and S. In Configuration A, because the participants sit side by side, the robot is not able to enter the p-space from adjacent approach directions. This is highlighted in Figure 3.6b.
Figure 3.6 – Configurations L and A with the robot present. The dashed quarter circle shows an assumed approximate boundary of the p-space. The images show that the robot is able to enter the p-space from directions adjacent to that of a participant, except in Configuration A.

When approaching the group from one of the eight positions around the periphery of the room, the robot moved towards the centre of the table in a straight line. The robot stopped moving when it was either as close as possible to, or in, the p-space of the group. Not only does stopping the robot in the p-space reinforce the idea that the robot is a social agent (Duffy, 2003; Lindner and Eschenbach, 2011), but the p-space defines a termination point that can be understood by the wizard without the use of guide markings on the floor, for example. Bounding the robot termination points to the p-space also provides a measure of consistency and repeatability across the experiment trials. To return to the periphery of the room, the robot turned on the spot and departed along the approach path.


3.7 Wizard of Oz

The experiment was designed with a Wizard of Oz (WoZ) paradigm to remove the temporal demand of developing a satisfactory navigation and control system. The use of WoZ also minimises the amount of modification required in the experiment space (reflective beacons, floor markings, etc), allowing for a more ‘natural’ room.

First introduced by Kelley (1983), the WoZ paradigm simulates intelligent systems and interfaces by using a person, often the experimenter, to replace part of the system’s functionality. Participants are not made aware of the experimenter’s role as a ‘Wizard’ before the experiment as this would alter their perception of the system. Typically WoZ is used in experimental designs when high quality empirical data is needed but gathering the data is not simple (Dahlbäck et al., 1993). The WoZ paradigm is often used when a system module is temporally or monetarily expensive to develop, or when achieving a particular level of performance for a system module is beyond the current state of the art. Scenarios where the WoZ paradigm has been used include natural language processing (Kelley, 1983; Green et al., 2006), non-verbal behaviour analysis (Lang et al., 2009; Mohammad et al., 2009), augmented reality (Dow et al., 2005; Weiss et al., 2009), user interface design (Taib and Ruiz, 2007; Mavrikis and Gutierrez-Santos, 2010), and robot navigation (Sirkin et al., 2015; Hüttenrauch et al., 2006).

One criticism of WoZ is that it can be used to ‘project into the future’ rather than be used in the process of iterative robot design (Bernsen et al., 1994; Dautenhahn, 2007). This criticism is supported by Riek (2014), claiming it is possible to predict a future state that will never be technically realised. Future predictions in this manner devalue the research as its goals or claims can never be achieved. Research using WoZ should therefore be conducted with a focus on progressing forwards and reaching a state of ‘good enough’, not on emulating a future capability that may never be achievable.

In a similar line of thought, Breazeal et al. (2005) suggests that the use of WoZ in experiments removes the opportunity to design autonomous robots that successfully mitigate errors that inevitably arise in human-robot interactions. This position aligns
with the more general commentary of Sabanovic et al. (2006): robots that interact with humans should be tested in the ‘real world’ with untrained members of the general public, and not in a laboratory setting, to truly measure the performance of the robot in question.

Fraser and Gilbert (1991) show that a participant’s awareness of the wizard has an effect on their perception of the robot and experiment. Participants who are aware of the wizard feel like they are interacting with a human through a proxy rather than with a robot. It is therefore accepted that participants should be unaware of the existence of a wizard, although this raises ethical concerns regarding how researchers can explain their experiment honestly without revealing the existence of a wizard. It is also possible that participants might feel foolish or be embarrassed on learning that they were deceived during the experiment, interacting with an agent that was different to the one they thought themselves to be interacting with.

The robot functionality replaced by the experimenter in this experiment is the navigation of the robot around the room and the cuing of audio prompts from the robot for the participants to answer the next question on the questionnaire. The trajectory of the robot, including the approach towards the participants to provide the audio cue, was designed to be algorithmic and ‘robotic’, and will be detailed in Section 3.8. A camera with a wide angle lens was mounted on the ceiling above the table to assist the wizard with navigation of the robot. Path planners for social robots have already been demonstrated in the literature (Kessler et al., 2011; Sisbot et al., 2010; Torta et al., 2011), verifying that this use of WoZ is not ‘projecting into the future’.

Having a robot navigation plan that is procedural and well defined means that the wizard has a clear and unambiguous sequence of actions to perform. Not only does this assist in the repeatability of navigating the robot, a desirable feature for inter-trial consistency, but it ensures that the wizard has a well defined and controlled role (Riek, 2012). To further improve consistency across the experiment trials, only one wizard was used, and several mock trials were performed before participant data was collected to minimise any variation in robot navigation due to the wizard acclimating with the system.
3.8 Experiment Conduct

At the start of each trial participant(s) were brought into the experiment space through the gap in the screens (Figure 3.3a) and seated in one of the four pre-set configurations (Figure 3.1). The robot was then manually wheeled into the space and placed in its starting location, the corner associated with Direction 1 (Figure 3.5) and oriented so that it could travel counter-clockwise around the room. The experiment and its objectives were then explained to the participants and they were also made aware of all sensors in the room and on-board the robot. Participants were not told which sensors were active, and were not provided any information on how the robot was to be controlled, but were told that only questionnaire data would be recorded and that all questions asked for non-identifying answers. Non-identifying information was obtained for ethical reasons, respecting the participants’ rights to privacy (Riek and Howard, 2014). When participants understood the experiment, the jigsaw task, and had completed the required consent form, the experimenter went from the room to the operator table (Figure 3.3a), and the trial began.

Referencing the pre-generated list of randomised approach directions, the experimenter used the overhead camera to assist with teleoperating the robot. The robot was driven one circuit around the periphery of the room and then continued to travel around the periphery to the first approach location. From this location the robot approached the table along a radial line as described in Section 3.6. When the robot finished its approach, it prompted the participants via an audio message to rate their comfort level with the robot’s most recent approach.

After a short pause the robot returned to the position on the periphery from where it had approached the group. The robot did not wait for participants to answer the questionnaire before returning to the periphery. From this location the robot repeated its navigation pattern of circling the periphery of the room before continuing to the next approach location. When this was completed for all eight approach directions, the robot continued to travel counter-clockwise around the periphery, returning to its original location in the corner associated with Direction 1. The experiment was
then complete and the experimenter returned to the room with a post-experiment questionnaire for each participant to complete.

### 3.9 Measurements

Participant responses were obtained using an in-experiment questionnaire and a post-experiment questionnaire. The in-experiment questionnaire collected self-reported comfort information from participants on robot approach while the post-experiment questionnaire was used to acquire data on participant demographics, task engagement and perception of the robot.

When the robot finished each approach to the group as described in Section 3.6, it prompted the participants via an audio message to “Please answer the next question on the form.” Each question was identical: “Please rate your comfort level regarding the robot’s most recent approach path”. Each question had a scale with 21 equally-spaced gradations for the participants to mark, with “Uncomfortable” at the left end and “Comfortable” at the right. This thesis uses the notion of a person’s ‘comfort’ being consistent with a natural language understanding of mental comfort as tranquil enjoyment and contentedness; as freedom from unease, anxiety and fear.

The post-experiment questionnaire was a composite of the NASA Task Load Index (TLX) questionnaire (Hart and Staveland, 1988) (6 questions), the Godspeed questionnaire (Bartneck et al., 2009) (24 questions), together with four qualitative questions on the robot approach directions and twelve questions on participant demographics. The NASA TLX questionnaire was used to measure how engaged participants were with the jigsaw puzzle task. The Godspeed questionnaire provided data on participant perception of different aspects of the robot. The qualitative questions asked which robot approach directions were least/most comfortable and why. These questions were asked to investigate whether participant responses during the experiment aligned with their post-experiment opinions. The demographic portion of the questionnaire asked about the age, gender, cultural background and education of the participants, and with their familiarity with computers, robots and virtual
agents. A question specifically asking whether participants thought that the robot was automated was also included. A full list of the questions can be seen in Appendix B.
Chapter 4

Statistical Theory

This chapter introduces the statistical theory that will be used for data analysis in this thesis. Motivation for the use of non-parametric statistics and a description of the difference between linear and directional statistics are introduced early in the chapter. Following these sections is a description of the linear and directional statistical methods used in the thesis. The chapter concludes with a section on the application of theory to the experimental data. This section covers estimation of the number of participants required to obtain statistically significant results from the experiment, how the data were pre-processed prior to analysis and the corrections applied to statistical results.

4.1 Parametric vs Non-Parametric Statistics

Methods of statistical analysis can be categorised as either parametric or non-parametric. Parametric analysis methods assume that the sampled population comes from a distribution with a known parameterization, such as the normal distribution. The objective of a parametric analysis is to use the sampled data to estimate the unknown distribution parameters, or to derive confidence intervals for the unknown parameters (Rao, 1983). Non-parametric methods differ in that they do not make assumptions
about the underlying distribution of a sample population. When using non-parametric
statistics the sampled data are often described as ‘distribution-free’ (Siegel, 1956).

4.2 Linear vs Directional Statistics

Statistical methods can also be categorised into linear (non-directional) or directional
methods. Linear methods are used for analysing scalar datasets while directional
statistics are used to analyse data that can be assigned an orientation (Mardia and
Jupp, 2009) or represented on a hypersphere (Mardia, 1972).

Functionally this means that data for each analysis type, linear or directional, is
sampled from different domains. Linear methods are used to provide a measure of
difference in magnitude for distributions sampled from the linear domain $(-\infty, \infty)$,
while directional methods are used to provide a measure of angular difference for data
sampled from the periodic circular domain $[0, 2\pi)$.

In this thesis linear statistical methods are used to analyse the distribution of par-
ticipant comfort ranks for particular defined robot approach directions. Directional
statistical methods are employed to analyse the distribution of a particular defined
rank across all eight robot approach directions, exploiting the relative orientations of
the robot approach directions. Linear statistical methods are also used to analyse the
post-experiment questionnaire responses.

4.3 Linear Statistics

4.3.1 Mann-Whitney U Test

The Mann-Whitney $U$ test (Mann and Whitney, 1947) is the non-parametric equiv-
alent of the Student $t$ test and is used for comparing two independently sampled
distributions (Freund and Wilson, 1993). The Mann-Whitney $U$ test is also equiva-
4.3 Linear Statistics

Lent to the Wilcoxon Rank Sum test (Wilcoxon, 1945); the two statistical scores are related through the linear transformation

\[ U = mn + \frac{m(m+1)}{2} - T \]

where \( U \) is the Mann-Whitney statistic, \( T \) the Wilcoxon statistic and \( m \) and \( n \) are the number of samples in the two distributions (Mann and Whitney, 1947).

The Mann-Whitney hypothesis

\[ H_0 : \tau_1 = \tau_2 \quad (4.1) \]

is that two samples under different treatment effects (\( \tau_x \)) have non-different results. \( H_0 \) is tested against the alternate hypothesis \( H_a \) that the treatment effects on the population are not equal (Hollander and Wolfe, 1973). To test the hypothesis a \( U \) statistic is obtained and then converted to an equivalent \( p \) value.

First the combined data from both distributions are ordered and assigned a corresponding rank from 1 to \( n_1 + n_2 \), where \( n_i \) is the number of data points in distribution \( i \). It does not matter whether the data are ranked in ascending or descending order; only the relative ordering of the data is important and this will be the same for an ascending and descending ranking method. In this step scores of equal value are assigned sequential ranks.

It is important to note that here the internal Mann-Whitney U-test ranking is not related to the form of the data being provided to it. In the present thesis the Mann-Whitney U-test performs a ‘ranking of ranks’ when provided with a set of participant comfort ranks for a robot approach direction.

The assigned ranks are then adjusted to account for any tied scores. The adjusted rank for each datum is the average of the initial ranks that had the same score. For example if four points of data had equal scores and were initially ranked 3, 4, 5 and 6, the new adjusted rank for each of these points would be \((3 + 4 + 5 + 6)/3 = 4.5\). Each
datum that has a unique score will retain its initial rank in this adjustment process. It does not matter if the new adjusted ranking for a datum is a non-integer value.

With a rank assigned to each datum, an intermediate statistic $U_i$ can be calculated for each distribution as follows:

$$U_1 = n_1 n_2 + \frac{n_1 (n_1 + 1)}{2} - \sum_{i=1} r_{i1}, \quad U_2 = n_1 n_2 + \frac{n_2 (n_2 + 1)}{2} - \sum_{i=1} r_{i2} \quad (4.2)$$

where $\sum r_{ij}$ is the sum of ranks for the $j$-th sample. The Mann-Whitney $U$ statistic is then defined as:

$$U = \min(U_1, U_2). \quad (4.3)$$

The Mann-Whitney $U$ statistic is approximately normally distributed which means that a $z$-value can be obtained (Sheskin, 2003). The $z$ estimate obtained from Equation 4.4 is compared to the critical $z$ value—the $z$ value associated with a significance value $\alpha$—to determine whether the two distributions are statistically different.

$$z = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}} \quad (4.4)$$

### 4.3.2 Kruskal-Wallis ANOVA

The Kruskal-Wallis one-way analysis of variance (KW-ANOVA) (Kruskal, 1952; Kruskal and Wallis, 1952) is an extension of the Mann-Whitney $U$ test and can be used to test hypotheses concerning multiple independent samples. A finding of significant difference in the KW-ANOVA result indicates that at least two of the data samples are significantly different. Determining which samples are significantly different can be done with a post-hoc pairwise comparison between each pair of data. The pairwise comparisons can be made using the Mann-Whitney $U$ test.
To test the (extended Mann-Whitney) hypothesis

\[ H_0 : \tau_1 = \cdots = \tau_k \]

against the alternate hypothesis, a process similar to that of the Mann-Whitney U test is followed.

Each datum is ranked against all others from the set of all data samples. These rankings are then used to provide an adjusted ranking for each datum (Section 4.3.1). An \( H \) statistic is then calculated as follows:

\[
H = \frac{12}{N(N+1)} \sum_{j=1}^{k} \left( \frac{\sum_{i=1}^{n_j} r_{ij}}{n_j} \right)^2 - 3(N + 1) \tag{4.5}
\]

where \( n_j \) is the number of data points in the \( j^{th} \) sample, \( N \) is the total number of sampled data points \( (N = \Sigma j n_j) \), and \( \Sigma r_{ij} \) is the sum of ranks for sample \( j \).

The \( H \) statistic from Equation 4.5 approximates a chi-squared distribution with \( k - 1 \) degrees of freedom. The hypothesis \( H_0 \) can then be rejected if \( H \geq \chi^2_{(k-1, \alpha)} \), where \( \chi^2_{(k-1, \alpha)} \) is the upper \( \alpha \) significance cut off level for a chi-squared distribution with \( k - 1 \) degrees of freedom. The hypothesis \( H_0 \) is accepted otherwise.

4.4 Directional Statistics

The two non-parametric directional analysis methods used in this work are discussed below. First, the Rayleigh test of uniformity takes a sample population distribution and provides a probability measure that the corresponding underlying distribution is uniform. The second test is a modified version of Watson’s \( U^2 \) test and provides a probability measure that multiple sample distributions were drawn from the same underlying directional distribution.
4.4.1 Rayleigh Test of Uniformity

The Rayleigh test (Mardia, 1972) estimates the probability that a population is uniformly distributed over all directions of interest. By treating each sampled datum in a given distribution as a unit vector in its corresponding direction, the magnitude of the vector sample mean $|\mathbf{R}|$ can be used as a measure of distribution uniformity. If the data are sampled from a uniform distribution and $\theta$ is the orientation of each datum, then the magnitude of the expected value of $|\mathbf{R}|$ is 0 as shown in Equation 4.6. The hypothesis of uniformity can therefore be rejected if the magnitude of $|\mathbf{R}|$ is ‘large’ (Mardia and Jupp, 2009).

$$E(\cos \theta, \sin \theta) = 0$$  \hspace{1cm} (4.6)

The magnitude of the vector sample mean can be determined as follows. Determine the sine $S$ and cosine $C$ components as

$$S = \frac{1}{n} \sum_{i}^{n} \sin \theta_i, \quad C = \frac{1}{n} \sum_{i}^{n} \cos \theta_i$$

where $n$ is the number of sampled data points and $\theta_i$ is the orientation of the $i$–th data point, as defined above. The magnitude of $R^2$ can then be calculated as

$$R^2 = C^2 + S^2.$$  \hspace{1cm} (4.7)

Although the magnitude of $R$ can be derived from Equation 4.7, $R^2$ is more useful. By construction, $R^2$ is a bivariate function similar to that of the chi-squared distribution with two degrees of freedom. Given an $R^2$ value, the chi-squared distribution can be used to approximate a $p$-value that quantifies the validity of the null hypothesis that the given distribution is uniform. The mapping to the chi-squared distribution is given by Mardia and Jupp (2009):

$$2nR^2 \sim \chi^2_2.$$  \hspace{1cm} (4.8)
It is worthwhile to note that the vector sample mean has the same orientation as
the resultant vector obtained by summing the sampled data. The difference between
these two vectors is that the vector sample mean is restricted to the space $[0, 1]$, while
the resultant vector is unbounded in the positive real space $[0, \infty)$. The magnitude of
the resultant vector is therefore directly influenced by the number of samples taken
from a distribution. Pathological cases aside, this means that the more samples that
are taken from a distribution that is not perfectly uniform, the greater the magnitude
of the resultant vector. This is obviously not desirable, and thus the vector sample
mean is used instead of the resultant vector.

Cox and Hinkley (1974) proved that the relationship in Equation 4.8 has an error
bound of $O(n^{-1})$. Jupp (2001) iterated on this relationship and demonstrated that
a modified version of the relationship has a tighter error bound of $O(n^{-2})$. The
modified relationship is shown in Equation 4.9. This relationship is preferred as there
is negligible error when mapping from $R$ to $\chi^2_2$, and Equation 4.9 is the mapping used
in this thesis.

$$ (1 - \frac{1}{2n})2n R^2 + \frac{nR^4}{2} \sim \chi^2_2 $$(4.9)

A final modification is made to the value of $R$ to accommodate situations where the
angular resolution of the data is coarse or the data are grouped. Stuart and Ord
(1994) defined a corrected value of $R$ as

$$ R^* = a(h)R, $$ (4.10)

where

$$ a(h) = \frac{h/2}{\sin(h/2)} $$ (4.11)
and \( h \) is the resolution of each group in radians. Typically this correction factor is only applied for groupings of \( \pi/4 \) or greater (Mardia and Jupp, 2009). Data with angular resolutions finer than \( \pi/4 \) have correction factors near unity. Substituting Equation 4.10 into 4.9 gives

\[
(1 - \frac{1}{2n})2na(h)^2R^2 + \frac{na(h)^4R^4}{2} \sim \chi^2
\]

where \( a(h) \) is defined in Equation 4.11. This final equation uses the vector sample mean of a sampled distribution to provide a \( p \)-value that estimates the probability that the underlying distribution is uniform. If the distribution is non-uniform then \( \theta \), the orientation of the vector sampled mean, provides an estimate of the angular mean of the distribution.

### 4.4.2 Watson’s \( U^2 \) Test

Watson’s \( U^2 \) test (Watson, 1961, 1962) is a method that can be used to test the null hypothesis that two sampled directional distributions come from the same underlying distribution. When used in this way, Watson’s \( U^2 \) test is the directional equivalent of the Mann-Whitney \( U \) test (Sheskin, 2003). The measure defined by Watson (1962) to test this null hypothesis with samples of size \( n \) and \( m \) is

\[
U_{n,m}^2 = \frac{nm}{n + m} \int_{-\infty}^{\infty} [F_n(x) - F_m(x) - \int_{-\infty}^{\infty} (F_n(y) - F_m(y))dF^*(y)]^2dF^*(x) \quad (4.13)
\]

where \( F_n(x) \) and \( F_m(x) \) are the empirical continuous distribution functions of the two samples and \( F^*(x) \) is the empirical continuous distribution function of the set of all \( n + m \) observations. This family of statistics is distribution free, independent of the underlying distribution and independent of the choice of origin for the cumulative distribution functions, unlike a possible alternative, the Cramér-von Mises \( W^2 \) measure.
The statistic defined in Equation 4.13 can only test the null hypothesis that two sampled distributions were produced from the same underlying distribution. Maag (1966) extended this measure to remove the limitation of testing only two sampled distributions, allowing for an analogue of an ANOVA test. The extended measure tests the null hypothesis that $k$ sampled distributions, $F_1(x), \ldots, F_k(x)$ come from the same underlying distribution. By defining $S_j(x)$ as the sampled cumulative distribution function of $F_j(x)$, and

$$S_N^*(x) = \sum_{j=1}^{k} \frac{n_jS_j(x)}{n}$$

where $n = n_1 + \cdots + n_k$ and $N$ is the set $(n_1, \ldots, n_k)$ as the sample cumulative distribution function of the set of all observations, Maag’s extended version of Watson’s $U^2$ statistic is defined as

$$U_{k,N}^2 = \int_{-\infty}^{\infty} \left( \sum_{j=1}^{k} n_j \left[ S_j(x) - S_N^*(x) - \int_{-\infty}^{\infty} (S_j(y) - S_N^*(y))dS_N^*(y) \right] \right)^2dS_N^*(x). \quad (4.14)$$

The $U_{k,N}^2$ statistic defined in Equation 4.14 assumes that the data are sampled at a ‘high’ resolution and are not grouped. To apply this statistic to data that are grouped or sampled at a coarse resolution, another modification is required. Brown (1994) shows how Equation 4.14 can be modified to account for grouped data and be presented in a form suitable for implementation. The resulting formula is a combination of a grouped analogue of Equation 4.14 and a correction factor to account for the grouping. Brown’s modified version of Watson’s $U^2$ statistic is briefly explained below for the purpose of implementation.

As before, there are $k$ samples of data, but now each sample is grouped into $m$ periods or sub-regions of the sampled domain. Let $O_{ji}$ represent the number of observations (data points) of the $j$-th sample in the $i$-th period. The expected number of observations in each period is then
4.4 Directional Statistics

\[ E_{ij} = n_j \frac{T_i}{N} \]

where

\[ T_i = \sum_{j=1}^{k} O_{ij} \]

is the total number of observations in period \( i \), and \( N \) is the total number of data points. The size of period \( i \) is \( \Delta_i \), where all \( \Delta_i \geq 0 \) and \( \Delta_1 + \cdots + \Delta_m = 1 \). Typically all periods are the same size, but construction this way allows for control over the size of individual periods where necessary. The correction factor can then be defined as

\[ U_{cf}^2 = (k - 1) \sum_{i=1}^{m} \frac{\Delta_i^2}{6} (1 - \frac{\Delta_i}{2}) + \frac{1}{12} k \sum_{j=1}^{k} n_j^{-1} \sum_{i=1}^{m} \Delta_i (O_{ji} - E_{ji})^2 \quad (4.15) \]

and represents a measure of the relative distortion of the original ungrouped \( U^2 \) distribution.

In the \( j \)-th sample, the \( i \)-th midpoint of the accumulated differences between the observation and the expected values is defined as

\[ Y_{ji} = \sum_{r=1}^{i-1} (O_{jr} - E_{jr}) + \frac{1}{2} (O_{ji} - E_{ji}), \]

and is used in the grouped analogue of Equation 4.14,

\[ U_{ga}^2 = \sum_{j=1}^{k} n_j^{-1} \left[ \sum_{i=1}^{m} \Delta_i Y_{ji}^2 - \left( \sum_{i=1}^{m} \Delta_i Y_{ji} \right)^2 \right] - N^{-1} \left[ \sum_{i=1}^{m} \left( \sum_{j=1}^{k} Y_{ji} \right)^2 - \left( \sum_{i=1}^{m} \sum_{j=1}^{k} Y_{ji} \right)^2 \right]. \]

Combining \( U_{cf}^2 \) and \( U_{ga}^2 \) will give the \( U^2 \) statistic.
\[ U_{k,N}^2 = U_{cf}^2 + U_{ga}^2 \]

\[ = (k - 1) \sum_{i=1}^{m} \frac{\Delta_i^2}{6} \left( 1 - \frac{\Delta_i}{2} \right) + \frac{1}{12} \sum_{j=1}^{k} \sum_{i=1}^{m} n_j^{-1} \sum_{i=1}^{m} \Delta_i (O_{ji} - E_{ji})^2 \]

\[ + \sum_{j=1}^{k} n_j^{-1} \left[ \sum_{i=1}^{m} \Delta_i Y_{ji}^2 - \left( \sum_{i=1}^{m} \Delta_i Y_{ji} \right)^2 \right] - N^{-1} \left[ \sum_{i=1}^{m} \left( \sum_{j=1}^{k} Y_{ji} \right)^2 - \left( \sum_{i=1}^{m} \sum_{j=1}^{k} Y_{ji} \right)^2 \right]. \]

(4.16)

The \( U^2 \) value obtained from Equation 4.16 provides a measure of how different the sampled grouped distributions are, with a larger \( U^2 \) value indicating a greater likelihood that at least two of the sampled distributions are different. This statistic can then be mapped onto the probability space \([0, 1]\) and compared to an \( \alpha \) value to determine whether two of the sampled distributions are significantly different.

Maag (1966) derived Equation 4.17 for mapping the \( U^2 \) value onto the probability space, where \( u \) is the \( U^2 \) value obtained from Equation 4.16, \( k \) is the number of sampled distributions and \( H_k \) is the Hermite polynomial of order \( k \). The series described in Equation 4.17 can be shown to be bound by a decreasing geometric series (Maag, 1966). The summation therefore only needs to be evaluated to a limit that provides sufficient accuracy.

\[ a_k(u) = \frac{2}{(2u)^{\frac{k}{2}} \sqrt{\pi}} \sum_{r=0}^{\inf} (-1)^r \binom{-k}{r} \exp\left(-\frac{(2r + k)^2}{8u}\right) H_{k-1}\left(\frac{2r + k}{2\sqrt{2u}}\right) \]

(4.17)

To obtain the \( p \)-value to compare against the \( \alpha \) chosen for significance, \( a_k \) is subtracted from 1 as shown in Equation 4.18. This is necessary as \( a_k \) is a probabilistic measure of difference, not similarity. Alternatively, it could have also been acceptable to require \( a_k \geq \alpha^* \), where \( \alpha^* = 1 - \alpha \) as the significance limit,

\[ p(u) = 1 - a_k(u). \]

(4.18)
4.5 Application of Theory

4.5.1 Number of Participants

The mean and standard deviation of two linear distributions, along with a desired statistical power level, are used to determine the required number of experiment instances that need to be performed for each seating configuration. Although these are concepts defined in a parametric sense, it is possible to use a statistical power efficiency measure to estimate the power of a non-parametric statistic relative to a parametric statistic. Once the number of experimental instances required to generate sufficient data for a parametric test is calculated, this value is then divided by the power efficiency measure to obtain the required number of experimental instances for a non-parametrical analysis of the data.

In this thesis the Mann-Whitney $U$ test and the parametric equivalent $t$-test are compared to estimate a corresponding power efficiency. The $t$-test is used due to its applicability to small data sets (de Winter, 2013), though non-parametric estimators are preferred (Siegel, 1956). The power efficiency of the Wilcoxon Rank Sum score, and thus the Mann-Whitney $U$ score (Wilcoxon, 1945), in comparison to the $t$-test can be greater than unity for distributions that are sufficiently far from normal (Lehmann and D’Abrera, 1975; Siegel, 1956). That is, for sufficiently non-normal distributions it is possible that the Mann-Whitney $U$ test is a more powerful discriminator than the standard parametric $t$-test. When the distributions are more normal, the power efficiency of the Mann-Whitney $U$ test relative to the $t$-test has a lower bound of 0.864 (Lehmann and D’Abrera, 1975). This conservative power efficiency estimate is used in this thesis to determine the number of experiment iterations required for each seating configuration.

Under the assumption that the comfort ranks are normally distributed for each robot approach direction—so that Students $t$-test may be applied—it is desirable to find two distributions that are identical except for a difference of mean rank not less than one which renders the two distributions statistically different. These two distributions
are conservatively assumed to have a standard deviation of 1.3 ranks. The value of 1.3 was chosen since a distribution with a mean comfort rank distribution of 4.5 (the mean of ranks 1 to 8) and a standard deviation of 1.3 would not span beyond the sampling domain. A standard significance level of 0.05 and statistical power of 0.8 were chosen.

Given that the required power of the test is set, it can be used to determine the number of required participants. Recalling that a Type II error is when the null hypothesis $H_0$ is false but accepted, and that the power of a statistical test increases with sample size, the sample size can be increased and statistical power re-estimated using the parameters defined in the previous paragraph until sufficient power is obtained.

Starting with a low estimated required sample size (e.g. $n = 3$), the critical values corresponding to the significance level for the $t_{n-1}$ distribution can be calculated for the two-tailed hypothesis test. Here $t_{n-1}$ defines a $t$ distribution with $n - 1$ degrees of freedom. If the mean of the second distribution lies outside of these critical values then we have the required difference between the two distributions. The second distribution is then modeled as a non-central $t$ distribution for power estimation (Cousineau et al., 2011), with the proposed difference of means and standard distribution influencing the non-centrality parameter (Evans et al., 1993). To reject this critical difference, the probability of sampling sufficiently far away from the mean has to equal or exceed the desired power such that, although a significant difference exists, it is not detected, thus satisfying the requirements for a Type II error. This process is iterated upon with an increasing number of samples until the desired statistical power is obtained.

The above process can be conveniently solved numerically in Matlab using the function `sampsizepwr`, obtaining a required participant count of 16 for each configuration. By dividing by the non-parametric efficiency of 0.864, an estimate of 18.5 participants required for each seating position in each configuration is obtained.

The number of trials for each configuration was set to 20.
4.5.2 Data Preprocessing

As individuals have different prior experiences, there will be differences between the comfort scores self-reported by different participants for the same experience in each experiment trial, where the participant experience is dependent on the seating configuration and robot approach direction. To account for this, participant responses were ranked from one (most comfortable) to eight (least comfortable). If two or more directions were scored equally they were assigned the same rank. The following score would then be set to one greater than the cardinality of previously ranked responses. By ranking the participant responses this way, it is expected that each rank will have a different population size due to the presence of ties. Following from this, given that there is no rank above Rank 1, it is further expected that Rank 1 will have the largest population size.

Each directional distribution was formed by counting how many times the associated rank was assigned to each robot approach direction. It is for this reason that equal participant responses are ranked with equal highest ranks rather than taking the average of the allotted ranks. There are always eight directional distributions for a particular seating position and these correspond to the eight comfort ranks. This ranking process was only performed on the self-reported participant comfort data.

As described in Chapter 3, there were eight robot approach directions equi-spaced around the participants. The directions 2, 3, ..., 8, 1 in Figure 3.3b were assigned angles $0, 7\pi/4, \ldots, 2\pi/4, \pi/4$ for the directional analyses. The angle assigned to each direction is arbitrary as the directional tests are rotationally invariant, but it is required that the relative ordering of the angles is maintained. As the angle between adjacent robot approach directions is $\pi/4$, the correction factor defined in Equation 4.10 is used with $h = \pi/4$.

It is also important to note that the Rayleigh test measures the uniformity of a given distribution through the mapping of a score from the vector sample mean space $\mathbb{R}^+$ to a value in probability space $[0, 1]$. Several non-uniform distributions will give an $R$
value close to 0, ‘passing’ the Rayleigh test. One example is a bi-modal distribution with peaks $\pi$ radians apart. A post-hoc inspection of results with low $p$-values will disclose these instances.

### 4.5.3 Post-hoc Correction Factor

For a given $\alpha$, the probability of making a Type I error (incorrectly rejecting the null hypothesis) is

$$1 - \alpha.$$  

If a family of tests is performed on the data set, the probability of not making a Type I error becomes

$$(1 - \alpha)^F,$$  \hspace{1cm} (4.19)

where $F$ tests are performed (Abdi, 2007). The term 4.19 approaches 0 as $F$ approaches infinity, so that the probability of making a Type I error approaches 1 as the number of tests performed increases. A correction factor is required to compensate for the growth in the probability of committing a Type I error. The Bonferroni-type correction factor (Simes, 1986; Worsley, 1982) is a common family-wise error rate (FWER) correction factor and sets a new family-wise significance level $\alpha_{FWER}$ by dividing the uncorrected $\alpha$ by the number of tests performed. These types of correction factors are conservative and have a low probability of producing a Type I error, but as a consequence lose power due to the growth of Type II errors.

In this thesis the false discovery rate (FDR) is used as a correction factor (Benjamini and Hochberg, 1995). This test is more powerful than alternative FWER correction methods. The FDR correction factor can be applied once all tests are performed. The $p$ values for all $m$ pairwise comparisons are assigned a rank from unity to $m$, with 1 corresponding to the smallest $p$-value. A $p_k$ value is defined as a new cut-off
point for determining statistical significance where \( p_k \) is defined as the largest \( p_i \) for which

\[
p_i \leq \frac{i}{mq^*}. \tag{4.20}
\]

Here \( q^* \) is defined as the ratio of incorrectly rejected hypotheses to all rejected hypotheses. In this thesis a value of 0.05 is used for \( q^* \). All pairwise comparisons that have a \( p \)-value less than that of \( p_k \) invalidate the null hypothesis of being sampled from the same distribution and are considered to be statistically significantly different. If there are no \( p \)-values that meet the criteria of Equation 4.20, then all pairwise comparisons are considered to be not statistically different.
Chapter 5

Experimental Results

This chapter presents results of the experiment detailed in Chapter 3. Sections 5.1 to 5.3 present participant demographics, and their perception of the robot and the jigsaw puzzle task. The adequacy of randomising the robot directions of approach for each seating configuration is statistically demonstrated in Section 5.4. Intra-positional and inter-positional analyses of data for each configuration are presented in Sections 5.6 to 5.10. The intra-positional analyses compare distributions of data within a group or individual data set while the inter-positional analyses compare participant comfort distributions of one seating position against another. Finally, Section 5.11 investigates the uniformity of the circular rank distributions for each group and individual seating position. This information is used to quantify which directions a robot should approach a group of two people from.

5.1 Participant Demographics

The total participant count across all seating configurations was 180. Forty people participated in each of the Configuration O, L and A experiments, twenty in the single-person configuration experiments, and there were forty participants in the Configuration A trials where the robot travelled clockwise around the room. Each person participated in only one experiment trial.
Participant ages ranged from 18 to 73, with a mean age of 24.5 years and standard deviation of 8.3 years. Eighty of the participants were male (44%) and one hundred were female (56%). The mean number of participant siblings was 1.3, with a standard deviation of 1.1. Of the 180 participants, 144 (80%) expressed a belief via the post-experiment questionnaire that the robot was automated and not controlled by a person.

Table 5.1 shows the level of education completed by all participants. The majority of participants had either completed a Bachelor’s degree or year 12 of high school, the final high school year in Australia. These participants are likely to be in the process of completing a Bachelor’s degree given that participant recruitment was conducted on a university campus.

Recruited participants also reported their origins from a wide variety of countries. For the purposes of data presentation, these countries were grouped into geographical regions. The distribution of participant origin can be seen in Figure 5.1.

It should be noted that a statistical analysis of differences between sampled participants (such as with age, sex, education, etc.) and how these differences influence participant responses cannot be made with statistical rigor given the amount of data obtained in this experiment. For instance, to investigate the effect of the sex of the participants, it would be necessary to double the number of Configuration S experiments so there were 20 instances of each sex. For each of the paired configurations, it would be required to quadruple the number of experiments performed so that all permutations of seating arrangements (male, male), (male, female), (female, male) and (female, female) were tested. The pairing of male with female is present twice to test for differences based on the relative positions of the two participants. To test just this one difference increases the number of participants required to 680. Accounting for other potential differences would further increase the required number of participants. Performing experiments with this number of participants is not feasible within the time frame of the thesis.
5.1 Participant Demographics

Table 5.1 – Level of completed education for all participants.

<table>
<thead>
<tr>
<th>Level of completed education</th>
<th>Number of participants</th>
<th>Percentage of all participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 12 or less</td>
<td>83</td>
<td>46%</td>
</tr>
<tr>
<td>Trade Certificate</td>
<td>4</td>
<td>2%</td>
</tr>
<tr>
<td>Diploma</td>
<td>15</td>
<td>8%</td>
</tr>
<tr>
<td>Bachelor’s degree</td>
<td>62</td>
<td>34%</td>
</tr>
<tr>
<td>Master’s degree</td>
<td>7</td>
<td>4%</td>
</tr>
<tr>
<td>PhD</td>
<td>9</td>
<td>5%</td>
</tr>
</tbody>
</table>

Figure 5.1 – Graph of participant birthplace, grouped by geographical region.
5.2 Participant Perception of the Robot

It is of interest to see how participant perceptions of the robot change from when the participant is alone with the robot, to when they are in a group of two. To test for these differences, responses of participants were first collated for each question of the Godspeed questionnaire (Bartneck et al., 2009). A KW-ANOVA test was then performed to compare participant responses across the different seating configurations. No significant differences were found for any of the Godspeed questions.

Two distributions were then generated for each question in the Godspeed questionnaire; a distribution for the grouped participants and a distribution for the lone participants. For each Godspeed question, the two distributions were compared using the Mann-Whitney $U$ Test. There were six questions where the responses of grouped and lone participants were significantly different. These questions required a response on a graduated scale between the following pairs of extremes:

- Fake — Natural
- Machine-like — Human-like
- Unconscious — Conscious
- Dead — Alive
- Mechanical — Organic
- Artificial — Life-like.

In all of these categories the means of the grouped participant responses were closer to the attributes listed on the right when compared to the responses of the lone participants. These results suggest that participants who were already engaged in an interaction, by virtue of the presence of the second person, were more receptive to viewing the robot as having some agency. In contrast, lone participants were more likely to view the robot as a tool or device. This observation of groups assigning more agency to robots than individuals has previously been reported by others (Yang et al., 2015).
5.3 Task Loading

The NASA-TLX questionnaire (Hart and Staveland, 1988) was included in the post-experiment questionnaire to assess participant perception of the jigsaw puzzle task. Participant responses to the questionnaire can be seen in Table 5.2. The goal of the task was to provide participants with a cognitive load for the duration of the experiment such that they were less aware of the location and movement of the robot.

Both the “mental demand” and “required effort” fields had the majority of scores ranging from 2–4 out of 5, suggesting that moderate effort and mental demand were required for the jigsaw puzzle task. This provides empirical support for the proposition that the jigsaw puzzle was an engaging activity (Section 3.3) and therefore distracted participants from the position and movement of the robot to some extent.

The majority of participant responses in the “performance” field were from 2–3, suggesting that participants felt they had moderate success working on the jigsaw puzzle. More than half of the participants assigned a score near unity for the “temporal demand” field. With no group completing the jigsaw in the allotted experiment time, these results suggest that participants felt some level of success working on the jigsaw puzzle while feeling no compulsion to complete it prior to the conclusion of the experiment.

A comparison between the responses of grouped and lone participants was also performed for the questions in the NASA-TLX questionnaire. The method of analysis was the same as is described in Section 5.2. In the initial KW-ANOVA test across the group configurations there was a significant difference only for the question about participant perception of their performance ($\chi^2(2,117) = 7.40$, $p = 0.02$, $\eta^2 = 0.06$). After the subsequent multiple comparison analysis, the only significant difference that remained was between Configurations L and A. Participants from Configuration A reported higher levels of performance than did the participants seated in Configuration L.
The following analysis comparing paired and lone configurations showed that lone participants found the jigsaw puzzle more physically and temporally demanding, and that they also experienced greater levels of frustration with the task. With no significant differences found for the reported success in working on the jigsaw puzzle between the grouped and lone participants, these results suggest that lone participants worked harder than their paired counterparts to achieve a similar level of performance.

Table 5.2 – Results from the NASA-TLX questionnaire. The scores for each of the 180 participants have been rounded to the nearest integer for each row.

<table>
<thead>
<tr>
<th>Score</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Mental Demand</td>
<td>30</td>
<td>46</td>
<td>40</td>
<td>48</td>
<td>16</td>
</tr>
<tr>
<td>High Mental Demand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Physical Demand</td>
<td>21</td>
<td>52</td>
<td>55</td>
<td>44</td>
<td>8</td>
</tr>
<tr>
<td>High Physical Demand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Temporal Demand</td>
<td>102</td>
<td>57</td>
<td>17</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>High Temporal Demand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Performance Level</td>
<td>33</td>
<td>65</td>
<td>47</td>
<td>29</td>
<td>6</td>
</tr>
<tr>
<td>High Performance Level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Effort</td>
<td>21</td>
<td>52</td>
<td>55</td>
<td>44</td>
<td>8</td>
</tr>
<tr>
<td>High Effort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Frustration</td>
<td>50</td>
<td>59</td>
<td>42</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>High Frustration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.4 Randomisation of Robot Approach Directions

The order of robot approach directions was randomised to decouple temporal bias from particular robot approach directions (Section 3.8). A proposed unique random order of robot approach directions was generated for all experiment trials. This was done before any trials were performed to ensure that the occurrence of each robot approach direction was uniformly distributed across the set of all robot approach events for all experiment trials. Participant comfort scores were then analysed to determine whether temporal bias was observed. Results of this analysis show there was no temporal bias in the participant comfort responses and therefore the order of robot approach directions did not statistically influence participant comfort responses. The complete analysis is presented in Appendix C.
5.5 Inter-position Comparison

Participant comfort results are analysed in Sections 5.6 to 5.10. Part of the analysis involves an inter-positional comparison of data between two seating positions. To perform this analysis, the relative robot approach directions are labelled as shown in Figure 5.2. This labelling of directions is performed here such that robot approach directions that are the same relative to the seating position for each data set have the same assigned numerical label.

![Figure 5.2 – Direction labels for data rotated for inter-positional analysis.](image)

5.6 Configuration O

The seating arrangement designated “Configuration O” has two participants placed opposite each other across a square table.

5.6.1 Intra-position Comparison

The comparison of distributions within a group or individual data set.
5.6 Configuration O

**Linear Statistics:** There were no statistically significant differences between the distributions of comfort rank associated with each robot approach direction for the group data ($\chi^2(7,152) = 14.16, p = 0.05, \eta^2 = 0.09$), or for the bottom seating position ($\chi^2(7,152) = 14.11, p = 0.05, \eta^2 = 0.09$). Significant differences were found between participant comfort ranks of robot approach directions for the top seating position ($\chi^2(7,152) = 23.13, p < 0.01, \eta^2 = 0.15$). Table 5.3 shows $p$-values calculated from the post-hoc multiple comparison test, with significantly different pairs emphasised.

**Table 5.3** – The $p$-values listed in the table are the results from a post-hoc multiple pairwise comparison test on the distributions associated with each robot approach direction for the top seating position of Configuration O. The $p$-values set in bold show which corresponding pairs of robot approach directions had distributions that were statistically significant in their difference.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.01</td>
<td>0.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>0.00</td>
<td>0.01</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.08</td>
<td></td>
<td>0.68</td>
<td>0.75</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.21</td>
<td>0.78</td>
<td>0.25</td>
<td>0.01</td>
<td>0.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.88</td>
<td>0.11</td>
<td>0.02</td>
<td>0.00</td>
<td>0.11</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.28</td>
<td>0.42</td>
<td>0.05</td>
<td>0.00</td>
<td>0.26</td>
<td>0.61</td>
<td>0.37</td>
<td></td>
</tr>
</tbody>
</table>

**Directional Statistics:** For this configuration there were statistically significant differences for both the top ($U^2 = 1.24, p = 0.00$) and bottom ($U^2 = 1.01, p = 0.01$) seating positions. Table 5.4 shows the $p$-values of the post-hoc multiple pairwise comparison test, with the significantly different distributions emphasised. There were no statistically significant differences for the circular rank distributions of the group ($U^2 = 0.69, p = 0.21$).

### 5.6.2 Inter-position Comparison

The comparison of distributions across multiple seating positions.
Table 5.4 – These tables show the $p$-values resulting from the intra-position directional analysis of comfort rank distributions for the datasets that showed significant differences in Configuration O. The emphasised $p$-values show which corresponding circular rank distributions were found to be significantly different.

(a) Individual O left/top seating position

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.28</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.45</td>
<td>0.46</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.36</td>
<td>0.37</td>
<td>0.77</td>
<td>0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.09</td>
<td>0.05</td>
<td>0.12</td>
<td>0.04</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>0.02</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
<td>0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.23</td>
<td>0.56</td>
<td></td>
</tr>
</tbody>
</table>

(b) Individual O right/bottom seating position

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>0.04</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.72</td>
<td>0.22</td>
<td>0.11</td>
<td>0.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.86</td>
<td>0.30</td>
<td>0.09</td>
<td>0.47</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.16</td>
<td>0.61</td>
<td>0.01</td>
<td>0.08</td>
<td>0.19</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.00</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.21</td>
<td>0.13</td>
<td>0.09</td>
</tr>
</tbody>
</table>
Table 5.5 – Resulting $p$-values from the inter-position analyses of the two seating positions of Configuration O. Table (a) shows the $p$-value results for a linear pairwise comparison of distributions for each robot approach direction. Table (b) shows the $p$-value results for a directional pairwise comparison of rank distributions.

(a) Linear results of inter-position analysis for Configuration O.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.83</td>
<td>0.62</td>
<td>0.09</td>
<td>0.82</td>
<td>0.48</td>
<td>0.79</td>
<td>0.95</td>
<td>0.55</td>
</tr>
</tbody>
</table>

(b) Directional results of inter-position analysis for Configuration O.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.92</td>
<td>0.25</td>
<td>0.04</td>
<td>0.03</td>
<td>0.28</td>
<td>0.69</td>
<td>0.06</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**Linear Statistics:** There were no statistically significant differences for the pairwise comparison of the distribution of ranks between the two individual seating configurations for all robot approach directions. The results of the Mann-Whitney analysis can be seen in Table 5.5a.

**Directional Statistics:** Table 5.5b shows the $p$-values resulting from a pair-wise comparison of each circular rank distribution for the two individual seating positions of Configuration O. Although there are some rank distribution pairs that have a $p$-value less than 0.05, no pairs were found to be statistically different because of the applied correction factor.

### 5.6.3 Combining the Seating Positions

Configuration O is unique in that it is the only tested configuration where the relative location of the second person is the same for both seating positions. Section 5.6.2 showed that for all relatively similar approach directions and comfort ranks there were no statistically significant differences (Table 5.5). For these reasons a new ‘Individual O’ data set is generated for analysis by combining the data sets of the top and bottom seating positions of Configuration O. The data are combined by appending the data
associated with the robot approach directions of one seating position to the data of the relatively similar robot approach directions of the second seating position. For example, the data of the robot approach from behind one seating position would be appended to the data of the robot approaching the other person from behind. This allows for an analysis with effectively twice as much data.

A KW-ANOVA analysis on this new data set suggested that some pairs of distributions associated with robot approach directions were significantly different ($\chi^2(7,312) = 33.26, p < 0.01, \eta^2 = 0.10$). The ANOVA-equivalent test for the directional distributions also suggested that some were significantly different ($U^2 = 1.36, p = 0.00$). The resulting $p$-values from both post-hoc multiple comparison tests are shown in Table 5.6.

### 5.6.4 Configuration O Summary

While there is variation in participant responses for the two seating positions of this configuration (Tables 5.3, 5.4), the inter-positional results (Table 5.5) show that there are no statistically significant differences in the linear or circular distributions between the two seating positions. The lack of significant differences in the inter-positional analyses suggests the expected result, that data acquired from the two individual symmetrical seating positions are consistent with each other.

The analysis of linear data for Individual A (Table 5.6a) shows strong differences between Direction 4 of the robot approaches (robot approaches from directly behind the seating position) and all other robot approach directions. Figure 5.3 shows the distribution of comfort ranks for each robot approach direction. The distribution for Direction 4 shows the majority of participants assigned it the least-comfortable score. The fact that this distribution is significantly different to the other seven shows that participants had a strong preference for where the robot should not approach from. This preference is highlighted in the intra-position directional analysis where the distribution for Rank 8 is significantly different to almost all other comfort rank distributions (Table 5.6b). Figure 5.4 shows the directional distribution of Rank 8,
Table 5.6 – These tables show $p$-values from post-hoc multiple pairwise comparison tests on the Individual O dataset. Table (a) shows the pairwise comparisons for the linear distributions associated with robot approach directions and Table (b) shows the pairwise comparisons for the circular comfort rank distributions. The emphasised $p$-values show which pairs of distributions were found to be statistically significantly different.

(a) Linear pairwise multiple comparison test.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
<td>0.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td><strong>0.00</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.00</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.03</td>
<td>0.72</td>
<td>0.89</td>
<td><strong>0.00</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.17</td>
<td>0.40</td>
<td>0.65</td>
<td><strong>0.00</strong></td>
<td>0.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.68</td>
<td><strong>0.01</strong></td>
<td>0.03</td>
<td><strong>0.00</strong></td>
<td>0.03</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.56</td>
<td>0.07</td>
<td>0.12</td>
<td><strong>0.00</strong></td>
<td>0.16</td>
<td>0.37</td>
<td>0.42</td>
<td></td>
</tr>
</tbody>
</table>

(b) Directional pairwise multiple comparison test.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.59</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.73</td>
<td>0.29</td>
<td>0.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.81</td>
<td>0.60</td>
<td>0.76</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
<td>0.03</td>
<td>0.06</td>
<td>0.38</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>0.28</td>
<td>0.17</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.02</strong></td>
<td><strong>0.03</strong></td>
<td></td>
</tr>
</tbody>
</table>

with Direction 4 being nominated as the least-comfortable direction in the majority of the experiment trials.
Figure 5.3 – The linear distributions of comfort ranks for each robot approach direction for the Individual O data set.
It is unsurprising that there are no significantly different distribution pairs for the group data of this configuration. As both participants are treated as having equal weighting for the group scores, with participants directly opposite each other, the high comfort scores of one seating position for a particular direction counter the low comfort scores of the other seating position, resulting in an averaging effect for all comfort distributions. This interpretation is supported by the intra-position directional analysis for the group. In fact, all directional rank distributions for the group data have to be close to uniform. This follows from the fact that no rank distribution pairs are significantly different from each other and that there are also no significant differences in the linear distributions associated with each robot approach direction. This observation is further emphasised in Section 5.11.1 with the Rayleigh test for uniformity on the circular rank distributions.

Figure 5.4 – Directional distribution of Rank 8 for the Individual O data set.
5.7 Configuration L

The seating position designated “Configuration L” has two participants seated in an ‘L’ shape configuration about a table in the centre of the room.

5.7.1 Intra-position Comparison

The comparison of distributions within a group or individual data set.

**Linear Statistics:** The null hypothesis of no significant differences in participant comfort distributions for the tested directions of robot approach was not rejected in this seating configuration. The null hypothesis was verified at the KW-ANOVA stage for the seating position on the right ($\chi^2(7,152) = 13.49, p = 0.06, \eta^2 = 0.09$); at the FDR correction stage for the seating position on the left ($\chi^2(7,152) = 17.69, p = 0.01, \eta^2 = 0.11$); and for the group comfort distributions ($\chi^2(7,152) = 17.53, p = 0.01, \eta^2 = 0.11$).

**Directional Statistics:** There were no statistically significant differences between the directional distributions of participant comfort rank in this seating configuration. This was true for the rank distributions of the left seating position ($U^2 = 0.84, p = 0.05$), the right seating position ($U^2 = 0.74, p = 0.13$), and the group directional rank distributions ($U^2 = 0.82, p = 0.06$). The null hypothesis was confirmed at the ANOVA-equivalent stage of analysis with all $p$-values greater than 0.05.

5.7.2 Inter-position Comparison

The comparison of distributions across multiple seating positions.
Linear Statistics: The corrected Mann-Whitney $U$ test showed no significant differences between similar relative approach directions for the two seating positions of this configuration. Table 5.7a shows the $p$-values obtained from the Mann-Whitney $U$ test on these data.

Directional Statistics: The inter-position pair-wise circular rank distribution analysis between the two seating positions in this configuration showed no statistically significant differences. The obtained $p$-values can be seen in Table 5.7b.

Table 5.7 – Resulting $p$-values from the inter-position analyses of the two seating positions of Configuration L. Table (a) shows the $p$-value results for a linear pairwise comparison of distributions for each robot approach direction. Table (b) shows the $p$-value results for a directional pairwise comparison of rank distributions.

(a) Linear results of inter-position analysis for Configuration L.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.93</td>
<td>0.97</td>
<td>0.53</td>
<td>0.66</td>
<td>0.46</td>
<td>0.25</td>
<td>0.66</td>
<td>0.52</td>
</tr>
</tbody>
</table>

(b) Directional results of inter-position analysis for Configuration L.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.69</td>
<td>0.39</td>
<td>0.35</td>
<td>0.23</td>
<td>0.71</td>
<td>0.38</td>
<td>0.85</td>
<td>0.86</td>
</tr>
</tbody>
</table>

5.7.3 Configuration L Summary

Inter- and intra-positional analyses were performed on the participant comfort data for Configuration L. Directional and linear statistical methods were used for each analysis. In all analyses for each data set, no statistically significant differences were found. These results suggest that participants had no preferences for which directions the robot should, or should not, approach the pair from.
5.8 Configuration A

The seating position designated “Configuration A” has two participants seated side-by-side at a table in the centre of the room.

5.8.1 Intra-position Comparison

The comparison of distributions within a group or individual data set.

**Linear Statistics:** There were no statistically significant differences in participant comfort rank distributions for the left seating position of this configuration \(\chi^2(7,152) = 20.24, p < 0.01, \eta^2 = 0.13\). This was concluded at the FDR correction stage as the KW-ANOVA test yielded a \(p\)-value less than 0.05. There were significant differences between participant rank distributions for the right seating position \(\chi^2(7,152) = 32.40, p < 0.01, \eta^2 = 0.13\), and for the group \(\chi^2(7,152) = 37.26, p < 0.01, \eta^2 = 0.23\). The pairs of robot approach directions that were statistically different for these two data sets can be seen in Table 5.8.

**Directional Statistics:** There were no statistically significant differences between the circular rank distributions for the left seating position of Configuration A \((U^2 = 0.84, p = 0.05)\). In contrast, there were statistical differences for the circular rank distributions of the right seating position \((U^2 = 1.32, p = 0.00)\), and the group data \((U^2 = 1.35, p = 0.00)\). The \(p\)-values from the post-hoc multiple comparison test for each of these data sets can be seen in Table 5.9.

5.8.2 Inter-position Comparison

The comparison of distributions across multiple seating positions.
Table 5.8 – These tables show \( p \)-values from *post-hoc* multiple pairwise comparison tests on the Group A and Individual AR data sets. Table (a) shows the pairwise comparisons for the linear distributions associated with robot approach directions for Group A and Table (b) shows the results of the same test on the Individual AR data set. The emphasised \( p \)-values show which pairs of distributions were found to be statistically significantly different.

(a) Group A

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.02</td>
<td>0.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.76</td>
<td>0.39</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.19</td>
<td>0.19</td>
<td>0.23</td>
<td>0.00</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.52</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.69</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.01</td>
<td>0.28</td>
<td>0.18</td>
<td></td>
</tr>
</tbody>
</table>

(b) Individual AR

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.16</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.81</td>
<td>0.25</td>
<td>0.26</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.30</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.12</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.14</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.36</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.24</td>
<td>0.92</td>
<td>0.47</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.9 – These tables show the p-values resulting from the intra-position directional analysis of comfort rank distributions for the two data sets that showed significant differences, the group and right seating position data sets, in Configuration A. The emphasised p-values show which corresponding circular rank distributions were found to be significantly different.

(a) Group A

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.52</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.37</td>
<td>0.25</td>
<td>0.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.47</td>
<td>0.82</td>
<td>0.69</td>
<td>0.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td><strong>0.00</strong></td>
<td><strong>0.01</strong></td>
<td>0.09</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.06</td>
<td>0.03</td>
<td><strong>0.01</strong></td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.03</td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td>0.20</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

(b) Individual AR

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.10</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.40</td>
<td>0.11</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.54</td>
<td>0.25</td>
<td>0.53</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td><strong>0.01</strong></td>
<td><strong>0.00</strong></td>
<td>0.04</td>
<td>0.35</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.03</td>
<td>0.20</td>
<td>0.03</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.01</strong></td>
<td>0.05</td>
<td><strong>0.01</strong></td>
<td>0.14</td>
<td>0.48</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.10 – Resulting $p$-values from the inter-position analyses of the two seating positions of Configuration A. Table (a) shows the $p$-value results for a linear pairwise comparison of distributions for each robot approach direction. Table (b) shows the $p$-value results for a directional pairwise comparison of rank distributions.

(a) Linear results of inter-position analysis for Configuration A.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.10</td>
<td>0.66</td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
<td>0.10</td>
<td>0.67</td>
<td>0.64</td>
</tr>
</tbody>
</table>

(b) Directional results of inter-position analysis for Configuration A.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.07</td>
<td>0.59</td>
<td>0.56</td>
<td>0.58</td>
<td>0.26</td>
<td>0.65</td>
<td>0.90</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Linear Statistics: Table 5.10a shows that there were no statistically significant differences between the distributions of the two seating locations for each robot approach direction in Configuration A.

Directional Statistics: There were no statistically significant differences for the pair-wise comparison of relative circular comfort rank distributions between the two seating positions in this configuration. Table 5.10b shows the $p$-values obtained from Watson’s $U^2$ test.

5.8.3 Configuration A Summary

While the comfort responses of participants in the two seating positions in this configuration were not statistically different from each other (Table 5.10), results differed between the intra-positional analysis for both seating positions. The linear intra-position analysis for the left seating position showed no statistically significant differences, while the comfort of participants for almost all robot approaches were significantly different to their comfort at approaches from Direction 4 (directly behind the participant) for the right seating position. For the right seating position there is also a trend towards approaches from Directions 6, 7, & 8 causing significantly differ-
ent comfort level distributions to those from Directions 2 & 3 (Table 5.8b). For the directional intra-position results there were no statistically significant differences for the left seating position but there were significant differences for the right seating position. The post-hoc multiple comparison test showed differences in comfort between both the two most-comfortable rank distributions and the three least-comfortable rank distributions (Table 5.9b).

The intra-analysis for the group data (Tables 5.8a, 5.9a) showed significant differences similar to those found for the right seating position, but also showed several other significantly different pairs of distributions as well. When these results are considered with the inter-positional results—where both seating positions had no significant differences—it is suggested that the comfort data for the left seating position have differences in its distributions that are tending towards the larger, significant differences of the right seating position.

5.9 Configuration S

The seating position designated “Configuration S” has one participants seated at a table in the centre of the room.

5.9.1 Intra-position Comparison

The comparison of distributions within a group or individual data set.

Linear Statistics: The KW-ANOVA test suggested statistically significant differences in the comfort distributions for the robot approach directions in this configuration ($\chi^2(7,152) = 83.76, p < 0.01, \eta^2 = 0.53$). Table 5.11a shows p-value results of the post-hoc multiple comparison test and the pairs of robot approach directions that were statistically different.
Table 5.11 – Resulting $p$-values from post-hoc multiple comparison tests for Configuration S. Table (a) shows results for a linear comparison of distributions for pairs of robot approach directions. Table (b) shows results for the directional pairwise comparison of circular rank distributions. Pairs of data that are significantly different are emphasised.

(a) Linear comparison of distributions for the different robot approach directions.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.17</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.00</td>
<td>0.86</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.95</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.61</td>
<td>0.06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.58</td>
</tr>
</tbody>
</table>

(b) Directional comparison of the circular rank distributions.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.42</td>
<td>0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.05</td>
<td>0.03</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Directional Statistics: The ANOVA-equivalent test for the intra-position circular comfort rank analysis also suggested statistically significant differences for some pairs of rank distributions ($U^2 = 2.74, p = 0.00$). The $p$-values for the pairwise comparisons of all circular rank distributions are shown in Table 5.11b.

5.9.2 Inter-position Comparison

The comparison of distributions across multiple seating positions.
In Configurations O, L and A the inter-position analyses provided statistical comparisons between distributions of each seating position of that configuration. As there is only one seating position in Configuration S, the data from this seating position are compared to those of both seating positions for Configurations O, L and A. These analyses show quantitative differences in the comfort of a person when a robot approaches based on the presence and relative location of a second person.

**Linear Statistics:** Results from the comparison of robot approach directions between Configuration S and the individual seating positions of the group configurations are shown in Table 5.12a.

**Directional Statistics:** The circular distribution of each rank for Configuration S was also compared with the corresponding circular distributions of Configurations O, L and A. The \( p \)-values of these statistical analyses can be seen in Table 5.12b.

### 5.9.3 Configuration S Summary

There were several significantly different distributions for the inter-positional analysis of data. The linear results (Table 5.11a) show that the majority of the significant differences occur between robot approach directions where the robot is visible to the participant in one approach direction but not the other. In these cases the approach directions where the robot was visible to the participant were rated as more comfortable. The results of the linear analysis agree with similar experiments reported in the literature for this configuration (Dautenhahn et al., 2006; Walters et al., 2007). This agreement shows that the experiment design and conduct provides results that are consistent with those reported in the literature, providing a level of validation for the more novel group experimentation.

The intra-position directional analysis (Table 5.11b) shows that the rank distributions tend to cluster into two groups: rank distributions associated with high comfort levels and rank distributions associated with low comfort levels. This clustering shows a
Table 5.12 – These tables show the inter-positional $p$-values obtained by comparing Configuration S distributions against the equivalent distributions of the individual seating positions in the other configurations. Table (a) shows the $p$-values obtained by comparing distributions associated with robot approach directions. Table (b) shows $p$-values obtained by comparing the circular rank distributions of Configuration S against the equivalent rank distributions of individual seating positions in the other seating configurations.

(a) Linear comparison of distributions for the different robot approach directions.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con. O (L)</td>
<td>0.15</td>
<td>0.74</td>
<td>0.43</td>
<td>0.11</td>
<td>0.12</td>
<td>0.87</td>
<td>0.34</td>
<td>0.18</td>
</tr>
<tr>
<td>Con. O (R)</td>
<td>0.20</td>
<td>0.38</td>
<td><strong>0.01</strong></td>
<td>0.11</td>
<td><strong>0.00</strong></td>
<td>0.79</td>
<td>0.36</td>
<td>0.64</td>
</tr>
<tr>
<td>Con. L (L)</td>
<td>0.45</td>
<td>0.83</td>
<td>0.12</td>
<td>0.01</td>
<td>0.01</td>
<td>0.31</td>
<td>0.42</td>
<td>0.19</td>
</tr>
<tr>
<td>Con. L (R)</td>
<td>0.40</td>
<td>0.56</td>
<td>0.09</td>
<td><strong>0.00</strong></td>
<td>0.08</td>
<td>0.51</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Con. A (L)</td>
<td>0.26</td>
<td>0.29</td>
<td>0.02</td>
<td><strong>0.01</strong></td>
<td>0.39</td>
<td>0.30</td>
<td>0.13</td>
<td>0.70</td>
</tr>
<tr>
<td>Con. A (R)</td>
<td><strong>0.01</strong></td>
<td>0.08</td>
<td>0.40</td>
<td>0.13</td>
<td><strong>0.00</strong></td>
<td>0.35</td>
<td>0.27</td>
<td>0.30</td>
</tr>
</tbody>
</table>

(b) Directional comparison of the circular rank distributions.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Con. O (Top)</th>
<th>Con. O (Bottom)</th>
<th>Ind. O</th>
<th>Con. L (Left)</th>
<th>Con. L (Right)</th>
<th>Con. A (Left)</th>
<th>Con. A (Right)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.02</td>
<td>0.01</td>
<td>0.11</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>0.19</td>
<td>0.28</td>
<td>0.11</td>
<td>0.06</td>
<td>0.38</td>
<td>0.73</td>
</tr>
<tr>
<td>3</td>
<td>0.14</td>
<td>0.68</td>
<td>0.77</td>
<td>0.16</td>
<td>0.55</td>
<td>0.59</td>
<td>0.19</td>
</tr>
<tr>
<td>4</td>
<td>0.27</td>
<td>0.15</td>
<td>0.33</td>
<td>0.26</td>
<td>0.17</td>
<td>0.41</td>
<td>0.56</td>
</tr>
<tr>
<td>5</td>
<td>0.48</td>
<td>0.12</td>
<td>0.24</td>
<td>0.24</td>
<td>0.52</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>0.57</td>
<td>0.15</td>
<td>0.21</td>
<td>0.11</td>
<td>0.66</td>
<td>0.48</td>
<td>0.23</td>
</tr>
<tr>
<td>7</td>
<td>0.60</td>
<td>0.01</td>
<td>0.07</td>
<td>0.39</td>
<td>0.16</td>
<td>0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>8</td>
<td>0.73</td>
<td>0.47</td>
<td>0.50</td>
<td>0.69</td>
<td>0.16</td>
<td>0.21</td>
<td>0.40</td>
</tr>
</tbody>
</table>
level of consistency in participant responses in that circular distributions that have large rank differences have a low measure of similarity between the distributions.

Table 5.12 shows the measure of similarity between the distributions of participants in Configuration S against the other configurations. There are a few statistically different distributions between the lone and grouped participants in the linear analysis. The distributions that were significantly different varied when comparing the linear distributions of Configuration S with Configuration O, L and A. There were no statistically significant differences in the circular rank distributions when comparing the responses of the lone and grouped participants. Combining this finding with the results of Table 5.11 suggests that the comfort of a person when a robot approaches is influenced by both the presence and location of a second person. Since Table 5.12 shows a high level of similarity between grouped and lone participants, it follows that, while factors such as the presence of a second person can influence the comfort response of a participant when a robot approaches, there is an underlying comfort profile that is adhered to.

5.10 Configuration A-CW

This seating configuration is the same as Configuration A, except that the robot travelled clockwise around the room when viewed from above instead of counterclockwise.

5.10.1 Intra-position Comparison

The comparison of distributions within a group or individual data set.

Linear Statistics: There were no significant differences for the linear distributions of comfort ranks associated with robot approach directions for the right seating position ($\chi^2(7,152) = 20.62, p < 0.01, \eta^2 = 0.13$). There were statistically significant differences between distributions of comfort rank for the left seating position
Table 5.13 – Resulting p-values from intra-positional post-hoc multiple comparison tests for Configuration A-CW. Table (a) shows results for the left seating position of the configurations while Table (b) shows results for the group data. Pairs of data that are significantly different are emphasised.

(a) Configuration A-CW left seating position.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td><strong>0.00</strong></td>
<td>0.01</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.29</td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.06</td>
<td>0.41</td>
<td>0.46</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.15</td>
<td>0.58</td>
<td>0.88</td>
<td>0.14</td>
<td>0.16</td>
<td>0.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.22</td>
<td>0.77</td>
<td>0.55</td>
<td>0.04</td>
<td>0.07</td>
<td>0.97</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

(b) Configuration A-CW group data.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>0.00</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td><strong>0.00</strong></td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td><strong>0.00</strong></td>
<td>0.02</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>0.00</strong></td>
<td>1.00</td>
<td>0.43</td>
<td><strong>0.01</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.02</td>
<td>0.10</td>
<td>0.08</td>
<td><strong>0.00</strong></td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.24</td>
<td>0.18</td>
<td>0.13</td>
<td><strong>0.01</strong></td>
<td>0.23</td>
<td>0.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.03</td>
<td>0.17</td>
<td>0.10</td>
<td><strong>0.00</strong></td>
<td>0.31</td>
<td>0.79</td>
<td>0.69</td>
<td></td>
</tr>
</tbody>
</table>

$(\chi^2(7,152) = 19.38, p < 0.01, \eta^2 = 0.12)$ and the group data $(\chi^2(7,152) = 30.09, p < 0.01, \eta^2 = 0.19)$. The p-values from the post-hoc multiple comparison test for both of these data sets can be seen in Table 5.13.

**Directional Statistics:** There were statistically significant differences between circular distributions of comfort ranks for left $(U^2 = 1.09, p = 0.00)$, right $(U^2 = 1.030, p = 0.00)$ and group distributions $(U^2 = 1.15, p = 0.00)$ in this configuration. The post-hoc multiple comparison test for the three sets of distributions can be seen in Table 5.14.
Table 5.14 – Resulting p-values from directional intra-positional *post-hoc* multiple comparison tests for Configuration A-CW. Each table shows the p-value results obtained from running the multiple comparison test on a different data set. Pairs of data that are significantly different are emphasised.

(a) Configuration A-CW left seating position.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.53</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>0.56</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td><strong>0.01</strong></td>
<td>0.05</td>
<td><strong>0.01</strong></td>
<td>0.15</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.33</td>
<td>0.18</td>
<td>0.08</td>
<td>0.48</td>
<td>0.05</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.01</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.00</strong></td>
<td>0.06</td>
<td>0.17</td>
<td>0.65</td>
<td>0.20</td>
<td></td>
</tr>
</tbody>
</table>

(b) Configuration A-CW right seating position.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.57</td>
<td>0.81</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.27</td>
<td>0.20</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.66</td>
<td>0.78</td>
<td>0.66</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.67</td>
<td>0.63</td>
<td>0.59</td>
<td>0.38</td>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.03</td>
<td><strong>0.00</strong></td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
<td>0.15</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

(c) Configuration A-CW group data.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.56</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.67</td>
<td>0.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.28</td>
<td>0.28</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.10</td>
<td>0.09</td>
<td>0.12</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.42</td>
<td>0.80</td>
<td>0.27</td>
<td>0.40</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td>0.02</td>
<td>0.02</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.00</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.00</strong></td>
<td>0.01</td>
<td>0.03</td>
<td>0.08</td>
<td>0.77</td>
<td></td>
</tr>
</tbody>
</table>
5.10 Configuration A-CW

5.10.2 Inter-position Comparison

There are several inter-position analyses that should be evaluated when comparing participant responses between Configuration A and Configuration A-CW. The two seating positions of Configuration A-CW can be compared to provide a measure of similarity between them. Further comparison can be made between the seating positions of Configuration A and Configuration A-CW. Each seating location for Configuration A-CW can be compared to the same relative seating position of Configuration A, but also to the reflected data of the other seating location of Configuration A. These analyses allow for analysis into how changing the robot direction of travel changes participant comfort responses. The reflection of data was done about the axis defined by Directions 4 and 8.

**Linear Statistics:** The p-values from the five sets of linear inter-comparison results are shown in Table 5.15. In the comparison between the left and right seating position of this configuration, there is a statistically significant difference for the distributions associated with Direction 5. There are no statistically significant differences for any of the other comparisons.

**Directional Statistics:** Table 5.16 shows the p-values obtained from the directional inter-positional comparison of rank distributions associated with this seating configuration. There were no statistically significant differences in the tested comparisons.

5.10.3 Configuration A-CW Summary

The results from the intra-positional analyses for this seating configuration were different to those of Configuration A. When comparing comfort data distributions for the seating positions of Configurations A, A-CW and the reflected data of Configuration A-CW, only one statistically significant difference was found across all linear and directional inter-positional analyses. With a high level of similarity in the
Table 5.15 – Linear inter-comparison $p$-value results of Configuration A and Configuration A-CW.

(a) Configuration A-CW left seating position and Configuration A-CW right seating position.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.90</td>
<td>0.05</td>
<td>0.39</td>
<td>0.98</td>
<td>0.00</td>
<td>0.15</td>
<td>0.51</td>
<td>0.62</td>
</tr>
</tbody>
</table>

(b) Configuration A left seating position and Configuration A-CW right seating position reflected.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.51</td>
<td>0.06</td>
<td>0.80</td>
<td>0.68</td>
<td>0.88</td>
<td>0.43</td>
<td>0.61</td>
<td>0.41</td>
</tr>
</tbody>
</table>

(c) Configuration A right seating position and Configuration A-CW left seating position reflected.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.86</td>
<td>0.13</td>
<td>0.43</td>
<td>0.19</td>
<td>0.53</td>
<td>0.55</td>
<td>0.96</td>
<td>0.42</td>
</tr>
</tbody>
</table>

(d) Configuration A right seating position and Configuration A-CW right seating position.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.10</td>
<td>0.97</td>
<td>0.75</td>
<td>0.24</td>
<td>0.41</td>
<td>1.00</td>
<td>0.52</td>
<td>0.69</td>
</tr>
</tbody>
</table>

(e) Configuration A left seating position and Configuration A-CW left seating position.

<table>
<thead>
<tr>
<th>Direction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value</td>
<td>0.97</td>
<td>0.18</td>
<td>0.18</td>
<td>0.65</td>
<td>1.00</td>
<td>0.44</td>
<td>0.40</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Table 5.16 – Directional inter-comparison *p*-value results of Configuration A and Configuration A-CW.

(a) Configuration A-CW left seating position and Configuration A-CW right seating position.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.70</td>
<td>0.14</td>
<td>0.16</td>
<td>0.58</td>
<td>0.32</td>
<td>0.42</td>
<td>0.04</td>
<td>0.23</td>
</tr>
</tbody>
</table>

(b) Configuration A left seating position and Configuration A-CW right seating position reflected.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.90</td>
<td>0.76</td>
<td>0.58</td>
<td>0.89</td>
<td>0.10</td>
<td>0.71</td>
<td>0.05</td>
<td>0.85</td>
</tr>
</tbody>
</table>

(c) Configuration A right seating position and Configuration A-CW left seating position reflected.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.75</td>
<td>0.27</td>
<td>0.17</td>
<td>0.93</td>
<td>0.02</td>
<td>0.51</td>
<td>0.21</td>
<td>0.79</td>
</tr>
</tbody>
</table>

(d) Configuration A right seating position and Configuration A-CW right seating position.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.73</td>
<td>0.38</td>
<td>0.09</td>
<td>0.35</td>
<td>0.76</td>
<td>0.37</td>
<td>0.58</td>
<td>0.75</td>
</tr>
</tbody>
</table>

(e) Configuration A left seating position and Configuration A-CW left seating position.

<table>
<thead>
<tr>
<th>Rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.92</td>
<td>0.52</td>
<td>0.56</td>
<td>0.64</td>
<td>0.94</td>
<td>0.82</td>
<td>0.40</td>
<td>0.98</td>
</tr>
</tbody>
</table>
inter-positional analyses and no observed patterns in the intra-positional analyses of Configuration A and A-CW, there is no evidence to support the hypothesis that the direction of robot travel influenced the comfort values reported by participants.

Of Configurations O, L and A, the difference in intra-positional results was greatest for Configuration A. Given that changing the robot direction of travel had no apparent effect in Configuration A, it is expected that changing the direction of robot travel would not influence the comfort responses for people seated in Configuration O or L.

5.11 Rayleigh Uniformity Test

The Rayleigh test estimates the probability that a directional distribution is uniform. Tables 5.17a and 5.17b respectively show a $p$-value estimate of uniformity for each rank distribution of each seating configuration and the corresponding mean angle of each distribution. The rank number associated with statistically non-uniform distributions provides insight as to whether directions of robot approach near the corresponding mean angle should be preferred or avoided. As this analysis into the uniformity of participant comfort rank distributions is exploratory, a more relaxed critical $p$-value of 0.1 is chosen.

Mean angles can be computed for any circular distribution that has a non-zero vector sample mean, but have significance only when the underlying distribution is significantly non-uniform. For completeness, the mean angle for all rank distributions of all seating configurations have been included in Table 5.17b, but only the emphasised values have significance as they are associated with $p$-values that indicate non-uniform distributions.

The admittance of ties in participant comfort responses means that the directional distributions are independent. The admittance of ties ensures independence as they allow for the number of degrees of freedom to be the same as the number of distributions. Therefore a correction factor is not required as the performance of multiple independent tests does not increase the probability that a Type I error is made.
Table 5.17 – Results of (a) the Rayleigh test for uniformity and (b) the mean angles for all ranks in all group and individual seating positions. Columns O, L and A contain results for the comfort ranks of groups while the other columns contain results for individuals. The suffixes (L) and (R) denote the seating positions on the left and right of the pair. The significance of the mean angles can be determined from the corresponding Rayleigh test p-values in (a).

(a) Rayleigh test for uniformity results. The p-values show the probability that the distribution is uniform. Bold numbers denote distributions that were significantly non-uniform (p < 0.10)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Configuration O</th>
<th>L</th>
<th>A</th>
<th>O Ind.</th>
<th>L (L)</th>
<th>L (R)</th>
<th>A (L)</th>
<th>A (R)</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.93</td>
<td>0.23</td>
<td><strong>0.01</strong></td>
<td>0.13</td>
<td><strong>0.10</strong></td>
<td>0.39</td>
<td>0.15</td>
<td><strong>0.03</strong></td>
<td><strong>0.00</strong></td>
</tr>
<tr>
<td>2</td>
<td>0.35</td>
<td><strong>0.07</strong></td>
<td><strong>0.08</strong></td>
<td><strong>0.08</strong></td>
<td>0.70</td>
<td>0.36</td>
<td>0.30</td>
<td><strong>0.03</strong></td>
<td><strong>0.01</strong></td>
</tr>
<tr>
<td>3</td>
<td>0.46</td>
<td><strong>0.07</strong></td>
<td>0.83</td>
<td>0.17</td>
<td>0.92</td>
<td>0.13</td>
<td>0.56</td>
<td><strong>0.09</strong></td>
<td><strong>0.02</strong></td>
</tr>
<tr>
<td>4</td>
<td><strong>0.06</strong></td>
<td>0.58</td>
<td>0.48</td>
<td>0.94</td>
<td>0.27</td>
<td>0.27</td>
<td>0.42</td>
<td>0.90</td>
<td>0.84</td>
</tr>
<tr>
<td>5</td>
<td>0.56</td>
<td>0.36</td>
<td>0.41</td>
<td>0.48</td>
<td>0.60</td>
<td>0.99</td>
<td>0.21</td>
<td>0.49</td>
<td>0.17</td>
</tr>
<tr>
<td>6</td>
<td>0.78</td>
<td>0.30</td>
<td><strong>0.01</strong></td>
<td>0.36</td>
<td>0.54</td>
<td>0.20</td>
<td>0.31</td>
<td><strong>0.07</strong></td>
<td><strong>0.00</strong></td>
</tr>
<tr>
<td>7</td>
<td>0.98</td>
<td>0.26</td>
<td><strong>0.01</strong></td>
<td>0.11</td>
<td><strong>0.06</strong></td>
<td>0.49</td>
<td>0.14</td>
<td><strong>0.01</strong></td>
<td><strong>0.00</strong></td>
</tr>
<tr>
<td>8</td>
<td><strong>0.08</strong></td>
<td>0.41</td>
<td><strong>0.00</strong></td>
<td><strong>0.00</strong></td>
<td><strong>0.06</strong></td>
<td>0.12</td>
<td><strong>0.06</strong></td>
<td><strong>0.01</strong></td>
<td><strong>0.00</strong></td>
</tr>
</tbody>
</table>

(b) Mean angles (degrees) for the rank distributions of all group and individual seating positions.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Configuration O</th>
<th>L</th>
<th>A</th>
<th>O Ind.</th>
<th>L (L)</th>
<th>L (R)</th>
<th>A (L)</th>
<th>A (R)</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-86</td>
<td>21</td>
<td><strong>111</strong></td>
<td>108</td>
<td>4</td>
<td>47</td>
<td>48</td>
<td>141</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td><strong>16</strong></td>
<td><strong>63</strong></td>
<td><strong>88</strong></td>
<td>90</td>
<td>23</td>
<td>73</td>
<td>115</td>
<td>97</td>
</tr>
<tr>
<td>3</td>
<td>-119</td>
<td><strong>118</strong></td>
<td>125</td>
<td>93</td>
<td>45</td>
<td>100</td>
<td>90</td>
<td>53</td>
<td><strong>116</strong></td>
</tr>
<tr>
<td>4</td>
<td><strong>-149</strong></td>
<td>30</td>
<td>144</td>
<td>95</td>
<td>-32</td>
<td>155</td>
<td>150</td>
<td>-122</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>-113</td>
<td>84</td>
<td>60</td>
<td>138</td>
<td>45</td>
<td>-172</td>
<td>103</td>
<td>-10</td>
</tr>
<tr>
<td>6</td>
<td>-18</td>
<td>-136</td>
<td><strong>-56</strong></td>
<td>-78</td>
<td>-105</td>
<td>-117</td>
<td>-87</td>
<td><strong>-53</strong></td>
<td><strong>-99</strong></td>
</tr>
<tr>
<td>7</td>
<td>170</td>
<td>-135</td>
<td><strong>-98</strong></td>
<td>-62</td>
<td><strong>-168</strong></td>
<td>-88</td>
<td>-65</td>
<td><strong>-56</strong></td>
<td><strong>-89</strong></td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>-146</td>
<td><strong>-85</strong></td>
<td><strong>-96</strong></td>
<td>176</td>
<td>-101</td>
<td><strong>-124</strong></td>
<td><strong>-75</strong></td>
<td><strong>-99</strong></td>
</tr>
</tbody>
</table>
5.11 Rayleigh Uniformity Test

5.11.1 Configuration O

For the Individual O data set, the circular distributions for Rank 2 and 8 were statistically non-uniform. Figure 5.5 shows the mean angle of these rank distributions relative to the individual seating position. Rank 2 has a mean angle in front of the Individual O seating position, suggesting that this is a good region to approach the seating position from. The mean angle for Rank 8 is located behind the seating position and, following a similar argument, this suggests a region from which the robot should not approach the seating position.

It is interesting to note that the distribution for Rank 1 (Figure 5.6a) is not statistically uniform. Inspection of the Rank 1 distribution shows that it is platykurtic-like with a strong weighting towards the ‘frontal’ approach directions 7, 8 and 1. Nineteen of the forty people in this configuration rated at least three robot approach directions as the most-comfortable. The data points must therefore be spread, contributing to the platykurtic-like distribution. Steele and Chaseling (2006) demonstrated that, for the most common directional statistical methods, more than 150 sample points are required to identify a platykurtic distribution as statistically significantly non-uniform with a power greater than 0.8. The distribution for Rank 1 has 119 data points and a p-value of 0.13, so while the distribution is classified here as uniform, a Type II error is possible.

The distributions of Rank 4 and 8 were significantly non-uniform for the group data of Configuration O. The non-uniformity of Rank 8 is unsurprising given the results of the individual seating position, again with a mean angle behind one of the seating positions. Figure 5.6b shows the distribution of Rank 4. The distribution is asymmetric: notably, there are no data points in this distribution associated with robot approach directions that are either in front of, or behind, participant seating locations.
Figure 5.5 – Mean angle of the Rank 2 and 8 circular distributions relative to the seating positions for the individual data of Configuration O. The set of individual data was formed by rotating and appending the data of the unmarked chair to that of the marked chair.

Figure 5.5 shows that people are more comfortable when they are approached by a robot from a ‘frontal’ direction, and least-comfortable when they are approached from behind. If these results were duplicated and rotated 180° to consider the top seating position, the mean angles of the ‘comfortable’ rank distributions for one seating position overlap the mean angles for the ‘uncomfortable’ rank distribution of the other seating position. A robot should approach a group in this configuration from are either side of the group, minimising the maximum discomfort that would be experienced by a person.

5.11.2 Configuration L

Ranks 1, 7 and 8 were significantly non-uniform for the left seating positions of Configuration L. Figure 5.7 shows the mean angles of these distributions relative to the seating position. The mean angles for the two least-comfortable ranked distributions are located behind the seating position. The distribution of Rank 8 is shown in Figure 5.8b. A robot should not approach a group of this configuration from these regions as they are associated with the least-comfortable directions of robot approach for the left seating position. The mean angle of the Rank 1 distribution is directly in front of the left seating position, where the robot is readily visible. The mean angle of
Figure 5.6 – Circular rank distributions for Rank 1 of the Individual O data set and Rank 4 of the group data for Configuration O. The thick radial line denotes the mean angle of the non-uniform distribution. The mean angle for the Rank 1 distribution is not shown as this distribution is not statistically non-uniform. The Rank 1 distribution is also opposite to the mean angles associated with the two least-comfortable ranks. The distribution of Rank 1 (Figure 5.8a) for the left seating position is also platykuritic-like, with most of the data points associated with robot approach directions where the robot is visible.

There were no significantly non-uniform rank distributions for the right seating position of Configuration L.

For the rank distributions of the group data, the distributions of Ranks 2 and 3 were statistically non-uniform. Both distributions are unimodal, with the Rank 2 data weighted towards Directions 1 and 2, and the Rank 3 data weighted to Directions 6, 7 and 8. These rank distributions are shown in Figure 5.9. The distribution for Rank 1 is platykuritic-like and not significantly non-uniform, similar to the Rank 1 distribution for the Individual O data set.
If two people are seated in Configuration L then, based on the non-uniform distributions associated with the high comfort ranks for the group and individual data sets, a robot should approach from between directions 1 and 2. Similarly, from the low-comfort non-uniform rank distributions, a robot should avoid approaching the group from behind.

![Figure 5.7](image)

**Figure 5.7** – The mean angles of the three statistically non-uniform rank distributions of the left seating position of Configuration L.

### 5.11.3 Configuration A

For the right seating position, Ranks 1, 2, 3, 6, 7 and 8 had distributions that were statistically non-uniform (Table 5.17). The orientation of mean angles for the non-uniform distributions relative to the right seating position can be seen in Figure 5.10. The distributions for Ranks 1 and 8 are also shown in Figure 5.11.

The most-comfortable non-uniform rank distributions for the right seating position have mean angles near the ‘frontal’ robot approach directions, where the robot is visible to both participants. If a robot was to approach the group from the mean angle associated with one of the two most-comfortable ranks, the table would be positioned between the robot and participant. The mean angles associated with the three least-comfortable rank distributions are opposite the mean angles for the Rank 1 and 2 distributions and align with a region where a robot can gain close proximity with someone in the right seating position while remaining out of sight.
Figure 5.8 – Circular rank distributions for Rank 1 and 8 of the left seating position for Configuration L. The thick radial lines denote the mean angle associated with each circular distribution.

Figure 5.9 – Circular rank distributions for Rank 2 and 3 of the group data for Configuration L. The thick radial lines denote the mean angle associated with each circular distribution.
There is a similar, though less significant, trend for the left seating position. The distribution for Rank 1 is bi-modal (Figure 5.12a) with one peak at Direction 3 and the other at Direction 8. For both of these robot approach directions there is an object, either the table or the other seated person, physically interposed between the robot and left seating position. Similar to the right seating position, the distribution for Rank 8 is also non-uniform (Figure 5.12b) and has a mean angle corresponding to a region where robot approaches would result in the robot coming close to the participant, as well as not being visible during its approach.

With both seating positions of Configuration O having the same orientation relative to the experimental space, it is not surprising that the group results are similar to the individual results. For the group data, the two most-comfortable and three least-comfortable rank distributions are non-uniform. The mean angles for these distributions are shown in Figure 5.13 and the distributions of Rank 1 and 8 are shown in Figure 5.14. The Rank 1 and 2 distributions have mean angles that align with regions in front of the group where the robot is visible when approaching. Ranks 6, 7 and 8, the least-comfortable ranks, also had statistically non-uniform distributions with mean angles corresponding to regions behind the participants where the robot was not visible when approaching. These results suggest that people seated in this configuration are most-comfortable with robot approach directions from a ‘frontal’ direction where the robot is visible to both group members. Robot approach directions from behind, where the robot is not visible to either person, should be avoided.

5.11.4 Configuration S

The three most- and three least-comfort rank distributions were significantly non-uniform for Configuration S (Table 5.17). The mean angles of all non-uniform distributions relative to the seating position are shown in Figure 5.15.

The circular distributions for Ranks 1, 2 and 3 are all highly non-uniform, have a spread of data points across several ‘frontal’ robot approach directions with few or no data points associated with ‘rear’ robot approach directions. The distribution for
Figure 5.10 – The mean angles of the six statistically non-uniform rank distributions of the right seating position of Configuration A.

Figure 5.11 – Circular rank distributions for Rank 1 and 8 of the right seating position for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

Rank 1 is shown in Figure 5.16a. The mean angles align with regions where a robot approach would be visible to a person in the seating position. The spread of data points across the ‘frontal’ robot approach directions suggests that while a robot should approach a person from a ‘frontal’ direction, there is a level of tolerance in which directions the robot can approach from without lowering a person’s comfort. These results agree with those previously reported by Dautenhahn et al. (2006) and Walters
Figure 5.12 – Circular rank distributions for Rank 1 and 8 of the left seating position for Configuration A. The thick radial line denotes the mean angle for the non-uniform distribution. The mean angle for the Rank 1 distribution is not shown as this distribution is not statistically non-uniform.

et al. (2007). The results of the Rayleigh analysis however, disagree with the finding by Dautenhahn et al. (2006) that the front-diagonal robot approach directions are most-comfortable. This discrepancy could be explained by the fact that the present work allows for multiple directions to be identified as the most-comfortable while Dautenhahn et al. (2006) requires a unique direction to be chosen.

The Rank 8 distribution (Figure 5.16b) is weighted strongly towards direction 4, directly behind the seating position. The distributions for Ranks 6 and 7 are bimodal with peaks at robot approach directions 3 and 5. All of these distributions therefore have mean angles oriented behind the seating position (Direction 4). The non-uniform distributions of Rank 6, 7 and 8 suggest that lone individuals find robot approaches from a ‘rear’ direction the least-comfortable and thus they should be avoided.
5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configuration A.

Figure 5.14 – Circular rank distributions for Rank 1 and 8 of the group data for Configuration A. The thick radial lines denote the mean angle associated with each circular distribution.

5.12 Discussion

This chapter presented the data acquired from the experiment trials and results from statistical analysis of the data. Participant responses from the Godspeed and NASA-TLX questionnaires were analysed and results showed that grouped participants viewed the robot as more of a social agent and were less frustrated (Section 5.12 Discussion – The mean angles of the five statistically non-uniform rank distributions for the group data of Configure
5.12 Discussion

Figure 5.15 – The mean angles of the six statistically non-uniform rank distributions of Configuration S.

Figure 5.16 – Circular rank distributions for Rank 1 and 8 of Configuration S. The thick radial lines denote the mean angle associated with each circular distribution.

5.2) when working on the jigsaw puzzle task in comparison to lone participants. An analysis of participant responses to each of the questions was performed. The only statistically significant difference was for perceived participant performance on the jigsaw puzzle for Configurations L and A, with participants seated in Configuration A noting higher performance scores. With the exception of this solitary statistical difference, the consistency of participant responses for these questions and the change of participant responses for comfort when approached by the robot suggest that there
is no correlation between participant perception of the robot and the self-reported participant comfort levels when approached by a robot.

Analysis of the post-experiment questionnaires also showed that lone participants found the jigsaw puzzle more physically and temporally demanding than did paired participants, and they also experienced greater levels of frustration with the puzzle. One hypothesis for this observation is that paired participants felt that there was some level of assistance available to them with the task. While this this an interesting observation, analysis of this observation falls outside the scope of the thesis.

Participant comfort responses for each robot approach direction were then analysed. These data were analysed within and across the different seating positions for each of the group configurations. Both intra- and inter-positional analyses were performed and each of these analyses involved linear and directional statistical methods. An intra-positional analysis was performed on the data from Configuration S, but the inter-positional analysis was performed between the lone seating position of Configuration S and the two individual seating positions of the other configurations. The results of these analyses showed that not only did the presence of a second person influence the comfort responses of the first, but the location of the second person relative to the first also influenced comfort responses. The intra-positional results of Configuration S were consistent with previously reported results, suggesting a measure of consistency with previous experimental research. A set of experiment trials using Configuration A, but with the robot travelling in the opposite direction, was performed. Results from the analysis of these data showed that the direction of robot travel around the room did not influence participant comfort responses.

A Rayleigh test of uniformity was also performed on the circular rank distributions of each group and individual seating position. This test identified which rank distributions were non-uniform and also calculated an associated mean angle for each distribution. The results of the Rayleigh analysis showed that, for all configurations, a robot should approach from a direction that allows for good sight of the robot by both people and this direction should be centered on the largest unoccupied area of the p-space.
It is interesting to note that in Configuration L there were no statistical differences for either the inter-positional or intra-positional analyses yet some rank distributions are non-uniform. This suggests that the non-uniform rank distributions are only slightly so, and that participant preferences are not as pronounced in this seating configuration compared to the other paired seating configurations. The seating orientation of Configuration L has a large open p-space and the combined field of vision for participants in this configuration almost covers all robot approach directions. This means that Configuration L has a seating setup ‘halfway’ between Configuration O and Configuration A, having features from both configurations. This may explain the results of Configuration L being less pronounced than the other seating configurations.

In Configuration A an unexpected left-right asymmetry in participant comfort responses was found. To investigate this statistically-significant finding, a set of experiment trials was performed in Configuration A-CW. An initial hypothesis was that the direction of robot travel around the room was the cause for the asymmetrical results, however there was no evidence to support this hypothesis. Given the results of Configuration A, Configuration A-CW and the comparison of these results, the reason for the asymmetry cannot be explained. This peculiarity needs to be explored in future work.
Chapter 6

Conclusion

The main aim of this work was to develop an understanding of the comfort of seated, paired people when approached by a robot from a number of directions. This understanding was developed experimentally across three maximally-different seating configurations of two people. The experiment also included a configuration of a lone person approached by a robot, allowing for a direct comparison of comfort between people that are with another and people that are alone when approached by a robot. The data obtained from the experiment were analysed using linear and directional statistical methods. A key focus of this work was the collection and analysis of comfort data from experimental participants. Analysis of the comfort data showed how the comfort profile of a person when approached by a robot is influenced by the presence and relative location of a second person. The novel use of directional statistics allowed for the analysis of circular comfort rank distributions, coupling participant comfort responses with the physical robot approach directions.
6.1 Summary

Chapter 1 introduced the project and the goal of exploring the comfort of grouped people when they are approached by a robot. The fact that humans are socially intelligent and interactive creatures, the increase in presence of robots in social environments, and the need for these robots to approach people to initiate and complete tasks, were presented as motivation for the research.

Chapter 2 reviewed the literature of comfort models of individuals when approached by a robot. Prior experimental research showed that individuals favoured ‘frontal’ approach directions to ‘rear’ approach directions. When interacting with robots, people preferred a distance from the robot that lies in the proxemic ‘personal’ or ‘social’ region. Application of these comfort models to social navigation algorithms was demonstrated, and research in the more general field of social navigation was briefly explored to help provide a broader context for the use of human comfort models in social navigation algorithms. Research into the comfort of grouped people with an approaching robot were then reviewed. Most of the presented work was either introductory in nature, with sample sizes that resulted in statistical tests with low or negligible power, or used a robot that was known by experimental participants to be teleoperated, providing a different experience for them. The limited number of studies that explore group comfort when a robot approaches provide motivation for the in-depth experimental analysis of the present work.

Chapter 3 presented the design of the experiments performed in this thesis. Design parameters included the size and configuration of the group, the task required for the group to work on for the duration of the experiment, the design of the robot’s appearance and capabilities, and the choice of implementing a Wizard of Oz experimental paradigm. The chapter included an explanation of how each experiment trial was performed. Participant data were acquired through a series of questionnaires. Details regarding each questionnaire were covered in the relevant section within the chapter.
Chapter 4 presented the statistical tools used for analysing the experimental data. The chapter discussed why non-parametric statistical methods were chosen over parametric methods and the differences between linear and directional statistics. The linear Mann-Whitney $U$ test and the Kruskal-Wallis ANOVA test are described along with the directional Rayleigh test of uniformity and Watson’s $U^2$ test. The chapter also defined the required parameters for the statistical methods used in this thesis.

Chapter 5 presented analyses of the experimental data. Participant demographics and participant perception of the robot and the jigsaw puzzle task were the first data analysed. Participants who were grouped found the robot more human-like and alive than the lone participants did. The grouped participants were also less frustrated with the jigsaw puzzle and found it less physically and temporally demanding than the lone participants did. Participant responses showed that moderate amounts of effort and mental demand were required for the jigsaw puzzle task, suggesting that it provided a suitable distraction from the location and movements of the robot.

The participant comfort data for when the robot approached were then analysed. First, the comfort data were used to show that there was no temporal bias for the occupancy of a particular robot approach direction across all experiment trials and that there was also no temporal bias in participant comfort scores. An intra-positional and inter-positional analysis of comfort was then performed for each seating configuration. The results of these analyses demonstrated that the comfort responses of a person were influenced by the presence and location of a second person. Two data sets were generated for Configuration A, each with the robot travelling in a different direction around the periphery of the room for the duration of the experiment. A comparison of participant responses showed that the direction of robot travel—clockwise or counter-clockwise—did not have an influence on participant comfort responses. Each experiment configuration was then analysed using Rayleigh’s test of uniformity. The results of this analysis showed the most comfortable direction to approach single and paired people from aligned with the largest gap in the group’s p-space, and where the robot was visible to all people.
6.2 Contributions

The major contribution of this thesis was the design, conduct and statistically rigorous analysis of an experiment to investigate the comfort of pairs of people when they were approached by a robot, together with the findings that were demonstrated by the analysis. More specifically, the thesis contributions were:

- Design and conduct of an experiment to analyse the comfort of paired participants when they are approached by a robot. The experiment was performed over three maximally different seating configurations. Sufficient trials were performed for each configuration to ensure a high statistical power.

- Participant comfort responses to the different robot approach directions were related spatially through the use of directional statistics. This allowed for the analysis of robot approach directions across the descending ranks of participant comfort as opposed to the usual analysis of participant comfort distributions across different robot approach directions. By analyzing the uniformity of the directional distributions, the most suitable direction of robot approach to a pair of people was evaluated.

For two people seated opposite each other, robot approaches from either the direct left or right side minimised the discomfort experienced by a person. For two people seated in an ‘L’ shape at a square table the robot should approach from beyond the corner of the table furthest from both people. Finally, for two people seated side-by-side at a table, the robot should approach from a ‘frontal’ direction.

- It was demonstrated through the use of directional statistics that when either lone or paired people have a comfort preference for the robot approach direction, that preference clusters into two regions of ‘suitable to approach from’ and ‘unsuitable to approach from’. These regions are spatially disjoint from each other and show a systematic change in participant comfort with the change of robot approach direction.
6.3 Future Work

There are several potential avenues of future work that can extend from this thesis:

- Incorporate the comfort models developed in this work into social robot navigation algorithms so that a social robot could find the path to a pair of interacting people such that the interactants are least-uncomfortable. This problem could be explored in detail by changing the approach path based on a changing group formation, the identification of which groups should be approached and which should be avoided, and investigations of how “intelligent spaces” could be exploited to achieve these social robot navigation tasks.

- Repeat the experiment, but with three participants in each group. There was a difference in the responses of paired and lone participants in the present work. It would therefore be of interest to see if the presence of a third person would influence participant responses, or whether there would be no statistically significant difference in participant responses when further increasing group size. A hypothesis given the results of this thesis would be that participants would find open p-space regions as the most comfortable regions to have a robot approach them from. While the thought of increasing group size by one could be continued indefinitely, it is worth noting that the practicality and logistics of this line of experiments declines as group size increases as discussed in Section 3.1.
The Godspeed questionnaire showed that participants who undertook the experiment with another person rated the robot as being significantly more ‘human’ in a variety of categories than their lone-participant counterparts. Repeating the paired experiment but replacing the second participant with selected objects having differing levels of agency—such as a block, another robot, a sensor array, a telepresent human—could help to identify the features present in the second person that are apparently causing these different perceptions of the robot.

Repeat the experiment in a setting that is more “in the wild” (Sabanovic et al., 2006). Expanding the experiment to consider whether factors such as room location, density of people and position of the group in the room influence participant comfort with different robot approach paths or participant perception of the robot would assist in providing insight to potential robot design guidelines. Understanding circumstances that cause a change of participant perception could help identify corresponding features that could be detected by sensors.

The work in this thesis investigated the response of participants based on a robot’s direction of approach. It is of interest to see how increasing the proxemic related functionality of the robot would influence participant response. For example, if a robot approaching a person from behind provided an audio prompt before getting close, it may be possible to improve the comfort of the person. Alternatively it is possible that if such a robot was to approach from a frontal location, the audio warning that the robot was coming might be unnecessary and detract from a person’s perception of the robot. Therefore a study that explored sub-dimensions of the “proxemic space” is of interest. Such a study could provide an understanding of the influence of each proxemic factor and their combination.
List of References


van Berkel, N. (2013). How adjustments to the velocity and functional noise of a robot can enhance the approach experience. Proceedings of the Twente Student Conference on IT.


Appendix A

Ethics Forms

This appendix contains the pre-experiment information presented to participants prior to the experiment. There are three forms attached here:

- A promotional flyer. This flyer formed the main source of advertising to attract people interested in participating in the experiment.

- Participant Information Statement. This is a form that explains to the participant the objective of the experiment, the type of information collected, potential risks of partaking in the experiment and the rights of the participant as a volunteer. Participants are provided a copy of the form to keep.

- Participant consent form. Participants are required to sign this form before the experiment commences to verify that they are providing their consent to their participation in the experiment. The consent form details that the experiment has been explained to their satisfaction and reiterates the participants rights as part of the experiment.
You could help in robotics research!

Help make the robots of the future more friendly, intuitive and responsive.

Have you ever been frustrated by computers? Wished they were easier to use and understand?

We are doing experiments to investigate how people react as a group when they are approached by a robot.

The study will take approximately 20 minutes of your time. As a part of this study you will be asked to perform a simple task while in the presence of the robot. There will be no video recording of the experiment and you will be unidentifiable from the collected data.

If you would like to participate in the study, or would like to know more (unfortunately we can’t offer payment) please contact Adrian Ball by email: a.ball@acfr.usyd.edu.au
PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Human groups and robot approach paths: Comfort levels with approaching robots

You are invited to participate in a study of human-robot interactions conducted by Adrian Ball and A/Prof David Rye (both of the Centre of Social Robotics, Australian Centre for Field Robotics, University of Sydney) and A/Prof Mari Velonaki (Creative Robotics Lab, National Institute for Experimental Arts, COFA, University of New South Wales). We hope to learn about how comfortable groups of people are when approached by a mobile robot. You were contacted for this study through the details provided by you as a response to our public advertisement.

If you decide to participate, we will invite you to perform a number of simple tasks as part of a group of people while the robot is present. During these tasks a mobile robot will approach the group several times and ask you to fill in a question in a paper questionnaire provided by us. Upon completion of the tasks, we will invite you to complete the remaining questions in the questionnaire. These questions will assess your thoughts on the robot and the task, and will collect some demographic information. All questions are general and you will not be identifiable through your answers. Cameras and other sensors will be located in the room where you will perform the task, these devices will not be recording any information and are there only to assist the robot to navigate in the room.

The experiment will take about twenty minutes, during which time the robot will be moving around the room. We would like you to remain in the room with the robot for the duration of the experiment. We do not foresee any risks related to this experiment. If you feel uncomfortable, however, and you wish to terminate your participation in the experiment, you can leave the room at any time without giving any reasons.

Any information that is obtained in connection with this study will remain confidential and will be disclosed only with your permission. If you give us your permission by signing this document, we may publish the results in academic journals and books or present the findings at conferences. In any publication or presentation, information will be provided in such a way that you cannot be identified.

We are conducting academic research and request your participation as a volunteer. You are not under any obligation to consent. If you would like to be informed of these results and you supply us with an email address we will assist you to access them. We cannot and do not guarantee or promise that you will receive any benefits from this study.
Your decision whether or not to participate will not prejudice your future relations with the researcher(s), the University of Sydney, University of New South Wales or other affiliated research groups. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any questions after the experiment, Adrian Ball will be happy to answer them. Email: a.ball@acfr.usyd.edu.au. Any person with concerns or complaints about the conduct of a research study can contact The Manager, Human Ethics Administration, University of Sydney on +61 2 8627 8176 (Telephone); +61 2 8627 8177 (Facsimile) or ro.humanethics@sydney.edu.au (Email).

You will be given a copy of this form to keep.
PARTICIPANT CONSENT FORM

I, ..................................................................................[PRINT NAME], give consent to my participation in the research project

TITLE: Human groups and robot approach paths: Comfort levels with approaching robots

In giving my consent I acknowledge that:

1. The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction.

2. I have read the Participant Information Statement and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.

3. I understand that being in this study is completely voluntary – I am not under any obligation to consent.

4. I understand that my involvement is strictly confidential. I understand that any research data gathered from the results of the study may be published however no information about me will be used in any way that is identifiable.

5. I understand that I can withdraw from the study at any time, without affecting my relationship with the researcher(s), University of Sydney or University of NSW now or in the future.
Appendix B

Questionnaires

This appendix contains the two questionnaires that were completed by the experimental participants. Questionnaire 1 was completed by the participants during the experiment and asked the participants how comfortable they were with each robot approach. Questionnaire 2 was completed after the experiment and contained qualitative questions asking the participant to reflect on the different robot approaches, the Godspeed questionnaire (Bartneck et al., 2009) (Impression of the Robot), NASA-TLX questionnaire (Hart and Staveland, 1988) (Assessment of the Task) and demographic questions (Interaction with other Agents, Demographic Information).
Questionnaire 1

1. Please rate how comfortable you were with the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable

2. Please rate your comfort level regarding the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable

3. Please rate your comfort level regarding the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable

4. Please rate your comfort level regarding the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable

5. Please rate your comfort level regarding the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable

6. Please rate your comfort level regarding the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable

7. Please rate your comfort level regarding the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable

8. Please rate your comfort level regarding the robot’s most recent approach path
   Uncomfortable  | | | | | | | | | | | | | Comfortable
Questionnaire 2

Post Experiment Reflections

Which approach direction did you find most comfortable?

Why did you find this direction the most comfortable?

Which approach direction did you find least comfortable?

Why did you find this direction the least comfortable?
Impression of the Robot

Part 1: Anthropomorphism

Please rate your impression of the robot on these scales

<table>
<thead>
<tr>
<th>Scale</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake</td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td></td>
</tr>
<tr>
<td>Machinelike</td>
<td></td>
</tr>
<tr>
<td>Humanlike</td>
<td></td>
</tr>
<tr>
<td>Unconscious</td>
<td></td>
</tr>
<tr>
<td>Conscious</td>
<td></td>
</tr>
<tr>
<td>Artificial</td>
<td></td>
</tr>
<tr>
<td>Lifelike</td>
<td></td>
</tr>
<tr>
<td>Moving rigidly</td>
<td></td>
</tr>
<tr>
<td>Moving elegantly</td>
<td></td>
</tr>
</tbody>
</table>

Part 2: Animacy

Please rate your impression of the robot on these scales

<table>
<thead>
<tr>
<th>Scale</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead</td>
<td></td>
</tr>
<tr>
<td>Alive</td>
<td></td>
</tr>
<tr>
<td>Stagnant</td>
<td></td>
</tr>
<tr>
<td>Lively</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td></td>
</tr>
<tr>
<td>Organic</td>
<td></td>
</tr>
<tr>
<td>Artificial</td>
<td></td>
</tr>
<tr>
<td>Lifelike</td>
<td></td>
</tr>
<tr>
<td>Inert</td>
<td></td>
</tr>
<tr>
<td>Interactive</td>
<td></td>
</tr>
<tr>
<td>Apathetic</td>
<td></td>
</tr>
<tr>
<td>Responsive</td>
<td></td>
</tr>
</tbody>
</table>
Part 3: Likeability

Please rate your impression of the robot on these scales

- Dislike
- Unfriendly
- Unkind
- Unpleasant
- Awful
- Like
- Friendly
- Kind
- Pleasant
- Nice

Part 4: Perceived Intelligence

Please rate your impression of the robot on these scales

- Incompetent
- Ignorant
- Irresponsible
- Unintelligent
- Foolish
- Competent
- Knowledgeable
- Responsible
- Intelligent
- Sensible

Part 5: Perceived Safety

Please rate your impression of the robot on these scales

- Anxious
- Agitated
- Quiescent
- Relaxed
- Calm
- Surprised
Assessment of the Task

1. Mental Demand - How mentally demanding was this task?
   Very Low .................................................. Very High

2. Physical Demand - How physically demanding was the task?
   Very Low .................................................. Very High

3. Temporal Demand - How hurried or rushed was the pace of the task?
   Very Low .................................................. Very High

4. Performance - How successful were you in accomplishing what you were asked to do?
   Very Low .................................................. Very High

5. Effort - How hard did you have to work to accomplish your level of performance?
   Very Low .................................................. Very High

6. Frustration - How insecure, discouraged, irritated, stressed and annoyed were you?
   Very Low .................................................. Very High
Interaction with other Agents

1. How often do you use a computer?
   - Never
   - Every day

2. How often do you interact with robots?
   - Never
   - Every day

3. How experienced are you at designing and building robots?
   - No experience
   - Expert

4. How often are you exposed to virtual agents (e.g. computer games such as The Sims)?
   - Never
   - Every day

5. Do you have a pet or regularly interact with one? Please circle one:
   - Yes
   - No

6. Do you think the robot in this experiment was automated? Please circle one:
   - Yes
   - No
Demographic Information

What is your gender? Please circle one: Male Female

What is your age?

What is the highest level of education that you have completed? Please tick one box
- □ Year 12 or less
- □ Trade certificate
- □ Diploma
- □ Bachelor’s level degree
- □ Master’s level degree
- □ PhD

What country were you born in?

How many siblings did you grow up with?

What cultural group do you belong to?
Appendix C

Randomisation of Robot Approach

This appendix presents a statistical analysis of the order of the directions of robot approaches made during the experiment trials and the corresponding participant comfort scores to determine whether ordinal bias was present in participant comfort scores.

If there is temporal bias in participant comfort scores, this bias needs to be independent of the order of approaches taken by the robot. This means that across all experiments, the ordinal-occupance distribution of each approach direction must be uniform.

The order of robot approach directions for each trial was random and generated prior to any experiments being performed. This pre-generation of the order of robot approaches was a precautionary measure in case a different ordering was required. An ordinal-occupance distribution was generated for each robot approach direction. A Mann-Whitney $U$ test was performed to test the null hypothesis that all eight distributions were sampled from the same underlying distribution. The results ($\chi^2(7, 56) = 0.01, p = 1.00, \eta^2 = 0.00$) support this null hypothesis. If all directions of approach are sampled from the same underlying distribution, the underlying distribution must be uniform. Given that each approach direction occurs once per trial and that all approach directions have the same ordinal-occupance distribution, a non-uniform distribution is not possible.
Table C.1 – Chi-squared results for a Kruskal-Wallis ANOVA test on the ordinal comfort-rank distributions for the seven different seating locations. The null hypothesis was that there was no temporal bias in participant comfort responses. The ANOVA test verified this for all seating positions except for O (top), which was then verified with a post-hoc multiple comparison test.

<table>
<thead>
<tr>
<th>Config</th>
<th>$\chi^2(7,152)$</th>
<th>$p$</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O (bottom)</td>
<td>9.81</td>
<td>0.20</td>
<td>0.06</td>
</tr>
<tr>
<td>O (top)</td>
<td>16.96</td>
<td>0.02</td>
<td>0.11</td>
</tr>
<tr>
<td>L (right)</td>
<td>3.15</td>
<td>0.87</td>
<td>0.02</td>
</tr>
<tr>
<td>L (left)</td>
<td>4.62</td>
<td>0.71</td>
<td>0.03</td>
</tr>
<tr>
<td>A (right)</td>
<td>13.36</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>A (left)</td>
<td>3.41</td>
<td>0.85</td>
<td>0.02</td>
</tr>
<tr>
<td>S</td>
<td>2.71</td>
<td>0.91</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Distributions of participant comfort ranks are generated post-experiment. For this analysis, eight ordinal distributions were formed for each seating position—one for each comfort rank—as participant comfort profiles changed across seating positions. A Kruskal-Wallis ANOVA test was performed on each set of distributions, with a null hypothesis that, for each seating position, each distribution was sampled from the same underlying distribution. In other words, the null hypothesis claims there is no ordinal-related change in participant comfort responses. The results of these ANOVA tests are shown in Table C.1. Only the null hypothesis associated with the left seating position of Configuration O was rejected ($p < 0.05$) at this stage. Performing a post-hoc multiple comparison test with a false discovery rate correction for this seating position found no significant differences between any pair of distributions, showing that the null hypothesis cannot be rejected. The inability to reject the null hypothesis for all seating positions supports the claim that there was no ordinal-occupance bias in participant comfort responses.