How Should a Robot Approach Two People?

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Experiments were conducted to quantify the direction of robot approach that a pair of seated people find most comfortable. Three maximally-different seating configurations and eight directions of robot approach were considered. The data were analysed using Rayleigh’s test of uniformity, a directional statistics method. Results from 140 participants showed robot approach directions that minimise participant discomfort align spatially with regions that allow good sight of the robot by both people and are centred on the pair’s largest unoccupied area of p-space.

**Keywords:** robot approach, directional statistics, experimental human-robot interaction

1. **Introduction**

Robots are increasingly present in social environments (Christensen & Pacchierotti, 2005). It is important—and challenging—to provide robots in these environments with the capability to be ‘socially aware’ (Riek, 2014). One facet of this challenge is creating robots that are able to instigate an interaction with a person, so the robot is not required to wait passively for people to interact with it. It is important that the interaction is initiated in a socially acceptable way, as the initiation phase has a strong influence on the success of the subsequent interaction (Mead, Atrash, & Matarić, 2013).

Since humans are social creatures (Herrmann, Hernández-Lloreda, Hare, & Tomasello, 2007), they often gather to interact socially. Given this proclivity, it is important to understand how a robot should approach groups of people as well as how lone individuals should best be approached. This paper builds on the contributions of past works (Dautenhahn et al., 2006; Karremann et al., 2014; Walters, Dautenhahn, Woods, & Koay, 2007) by investigating which robot approach directions a pair of interacting people find most comfortable. Experiments were performed with pairs of people seated in three geometrical configurations and approached from eight different directions by a robot. Data from the experiments were analysed using directional statistics to provide a quantitative measure of the direction a robot should approach a pair of people from to maximise their comfort.

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Experiments were also conducted for a seating configuration with only one person.

To the authors’ knowledge, this is the first work to quantify the direction from which a robot should approach a pair of people to maximise their comfort. This work extends prior research through the use of directional statistics to compare participant comfort across different robot approach directions. The remainder of the paper is organised as follows: Section 2 reviews related research and Section 3 describes the experiment and how data were collected. Data transformation and directional statistical methods are described in Section 4, with results following in Section 5. Section 6 provides a discussion on the results, and Section 7 concludes the paper.

2. Background

Hall (1966) defined four spatial regions that people may occupy when interacting with each other, with the physical distance they prefer dependent on the closeness of the relationship between the interactants, amongst other factors. These regions were termed the “intimate”, “personal”, “social”, and “public” regions. Hall defined the extent of these regions as 0–0.46 m (intimate), 0.46–1.2 m (personal), 1.2–3.7 m (social), and 3.7–7.6 m (public). Investigations of how close people approach to a robot have shown that they maintain a distance that is similar to that when approaching another person (Hüttenrauch, Eklundh, Green, & Topp, 2006; Silvera-Tawil, Rye, & Velonaki, 2015; Walters et al., 2005), placing themselves at a distance that lies in either the personal or social zone. Walters et al. (2006) showed that when the roles are reversed and the robot approaches a person, people are generally more comfortable when the robot stops at a distance that lies in either the personal or social region. If the robot positions itself too close to a person, then the person will move away from the robot so that they are more comfortable (Sardar, Joosse, Weiss, & Evers, 2012). These results support the notion that people attribute some level of social agency to robots, as discussed by Reeves and Nass (1996).

When a robot approaches a person to initiate an interaction, the angle of robot approach relative to the person’s orientation also needs to be considered. Dautenhahn et al. (2006), Walters et al. (2007) and Ball, Rye, Silvera-Tawil, and Velonaki (2015a) have shown that people find robot approaches from ‘frontal’ regions to be the most comfortable, and robot approaches from ‘rear’ regions—where they cannot see the robot—to be the least comfortable. This trend was also observed to be independent of a participant’s personality traits, as found by Syrdal, Dautenhahn, Woods, Walters, & Koay (2006). Dautenhahn et al. (2006) reports that robot approaches from a front-left or front-right direction are the most comfortable, as they are often perceived to be less confrontational than a direct, front-on approach. This understanding of a person’s ‘comfort profile’ when approached by a robot has been incorporated into path planners that guide a robot’s approach to a person in a social environment (Kessler, Schroeter, & Gross, 2011; Sisbot, Marin-Urias, Broquere, Sidobre, & Alami, 2010; Torta, Cuijpers, Juola, & van der Pol, 2011).

Since humans are social creatures (Herrmann et al., 2007), we often gather in groups. It is therefore desirable to extend our understanding of how a robot should approach a person to the question of how a robot should approach a group of interacting people. Kendon defined the “F-formation”, or “facing formation” (Kendon, 1990; McDermott & Roth, 1978), to capture the phenomenon of how people orient themselves in a group. When forming a group, people overlap their transactional spaces, forming a joint transactional space that Kendon termed the “o-space”. The o-space is surrounded by the “p-space”, a region containing all members of the interaction, and surrounding this is the “r-space”. The r-space is a region outside the F-formation but influenced by it, such as a zone where someone might wait to join the interaction. The spatial arrangements that people establish with one another in an F-formation can vary, but an approximately circular arrangement is common for groups of three or more people (Kendon, 1990).

Althaus, Ishiguro, Kanda, Miyashita, and Christensen (2004) demonstrated that a robot can
actively maintain an F-formation with a group of people for the duration of an interaction but did not investigate scenarios where the robot initiated the interaction. The preferred placement of a robot within a group of people has been shown using online surveys to be influenced by the cultural background of the person choosing the placement (Joosse, Poppe, Lohse, & Evers, 2014).

One of the difficulties in extending the current understanding of the robot approach directions preferred by a lone individual to what a group finds most comfortable is the relative orientation that the group members adopt to form a shared transactional o-space. This can result in scenarios where a robot approach direction can be comfortable for one group member but uncomfortable for another.

Preliminary work on a robot approaching a pair of people was presented by Karreman et al. (2014). Karreman’s work is most similar to the work presented here but, as a pilot study, it lacks the volume of experimental data and depth of statistical analysis. Their work was extended by Ball, Silvera-Tawil, Rye, and Velonaki (2014) and Ball et al. (2015a), who demonstrated that the presence of a second person changed the ‘comfort profile’ of the subject, improving the comfort of robot approaches from behind the person. Analysis using directional statistics was introduced to the problem by Ball, Rye, Silvera-Tawil, and Velonaki (2015b).

Vroon et al. (2015) presented a study in which a telepresence robot approached a group of three people several times, allowing the development of several hypotheses that could be extended to group-robot interaction. While the work in Vroon et al. (2015) is related to ours in that we both investigate directions of robot approach towards groups of people, participant knowledge that a person controls the robot in the work of Vroon strongly delineates their study from ours. Fraser and Gilbert (1991) showed that the known presence of a human in the robot control loop significantly influences the behaviour of interactants.

3. Experiment design

An experiment was designed with the aim of measuring participant comfort when a robot approached a group of people. We hypothesised that the comfort of people sitting in pairs is different when they are approached by a robot from different directions and is influenced by their relative seating positions. Pairs of participants were seated in armchairs around a low table in configurations consistent with Kendon’s F-formation and were engaged in a shared non-turn-taking task. In each trial a robot approached the pair of participants from eight different directions in random order, and the participants recorded their comfort with that robot approach. Each subject participated in only one trial. The experiment is described in more detail in following subsections.

3.1 Wizard of Oz

The experiment was designed within a Wizard of Oz (WoZ) paradigm. Introduced by Kelley (1983), WoZ is used to simulate intelligent systems and interfaces by having a “wizard”—typically the experimenter—simulate a portion of the system’s purported functionality. Dahlbäck, Jönsson, and Ahrenberg (1993) showed that this paradigm is suitable when high-quality empirical data is required but gathering the data is not a simple task. When designing a WoZ experiment, it is important to consider the role of the wizard and ensure that this role is properly controlled for (Riek, 2012).

Although path planners for social robots exist (Kessler et al., 2011; Sisbot et al., 2010; Torta et al., 2011), the robot in this work was controlled by the experimenter to focus on acquisition of participant comfort data. This was done to reduce the time required to obtain experimental data. By restricting the wizard to controlling the robot’s trajectory, the present work can be extended to future experiments with higher levels of robot autonomy (Bernsen, Dybkjær, & Dybkjær, 1994; Dautenhahn, 2007). The robot was driven by the same wizard for all experiments, limiting the number of experiment variables that needed to be controlled. The robot was driven in a way that was
3.2 Seating configurations

Three maximally-different seating configurations of two people that conform to an F-formation, as defined by Kendon (1990), were used in this work and are depicted in Fig. 1. Pairs of participants either sat opposite each other, in an ‘L-shape’, or side-by-side. These seating arrangements are referred to as Configurations O (opposite), L (L-shaped), and A (adjacent) respectively. The participants were seated in identical low armchairs around a small square table. The armchairs were placed to locate the participants in a valid F-formation with a shared transactional space intended to be focused on a joint task situated on the table. A variation of the experiment with only one participant was also performed to yield single-person data under identical conditions as the main experiment, for comparison with prior single-person results. We refer to this as Configuration S (single person).

3.3 Group task

A group task was included in the experiment to provide a shared focus and cognitive load for the participants. The cognitive load was intended to distract participants from the presence and movement of the robot and to minimise anticipation of the robot’s approach. An ideal task would be engaging, have no turn-taking mechanism, have an easy-to-understand goal, and be temporally demanding. The task should have no turn-taking mechanism as this can afford participants some mental reprieve, potentially increasing the likelihood that they may focus their attention on the robot. The task should be temporally demanding so that it cannot be completed in an experimental trial. Tasks that fulfil these criteria have an increased chance of participants focussing on the task rather than on the robot when it approaches. The task chosen in this work was a three-dimensional jigsaw puzzle. The jigsaw puzzle meets the last three criteria, and the third dimension increases the novelty and complexity of the task.

3.4 Experiment space

The experiment space should be sufficiently large that the subregions through which the robot travels when approaching the group are of ample and similar size to prevent spatial bias in the results. The space should have multiple easily-accessible exits. If there is only one exit, it is possible that a participant may feel uncomfortable at the prospect of having to ‘confront’ the robot to leave the space (Karreman et al., 2014), which would again introduce a bias into the results. A six-metre square space with exits on three sides was used for the experiments. A plan of the experiment space can be seen in Fig. 2a.
3.5 Robot approach

For each trial the robot approached a pair of subjects once from each of eight different positions around the periphery of the room. These positions were equally spaced at 45 degree intervals as shown in Fig. 2b. The order of approach directions was random for each trial so that any bias in participant comfort response over the trial duration was independent of the robot approach directions.

When the robot approached the participants from one of the eight positions, it moved in a straight line towards the centre of the table. The robot stopped when it was either in the group’s p-space or when it was as close as possible to the p-space while avoiding a collision. The p-space was chosen as the target of the robot’s approach as it was assumed that the robot would be treated as a social agent, and should therefore conform to simple social rules such as proximity during an interaction. By making the p-space the target of the robot’s approach, the terminal points of the approaches are bound to a region perceived by the wizard to be the p-space, providing a measure of consistency for robot approaches across several trials. To return to the periphery of the room, the robot turned on the spot and departed along the approach path.

3.6 Robot design

The robot used in this work was an Adept Pioneer 3 DX motion platform fitted with an aluminium frame (Fig. 3). The frame supported a speaker and an Asus Xtion Pro Live RGB-D sensor. A laptop computer was fitted to the base of the aluminium frame. The height of the robot was chosen to be 1 metre to the top of the frame, the approximate height of an average person seated in one of the experiment chairs. This height was selected to suggest that the robot might have equivalent social status as the participants (Rae, Takayama, & Mutlu, 2013). The robot speed was approximately 0.8 metres per second.

The speaker was used so that the robot could prompt participants through the use of an audio cue. The audio cue was a pre-recorded spoken message that was altered to sound synthetic and gender neutral.

The RGB-D sensor was not used in the present work, and the tasks performed by the laptop computer could have been implemented on the robot. These devices were included on the robot for ‘future-proofing’, as it is conceivable that camera and laptop may be required in future experiments. A robotic system can be regarded as more than the sum of its parts (Brachman, 2006; Liu & Wu, 2001), and changing the appearance of the robot could change subject perception of the robot. Keeping the robot’s appearance constant avoids another control parameter for inter-experiment analysis.
3.7 Conduct of experiment trials

Participants were recruited through poster advertisement and word of mouth at the Paddington campus (UNSW Art & Design) of the University of New South Wales.

The participant(s) were brought into the experiment space and seated in one of the four configurations (Fig. 1). The robot was then manually wheeled into the space and placed in the corner associated with Direction 1 (Fig. 2b). While wheeling the robot into the experiment space may remove some social agency from the robot, it was done for practical reasons. Driving the robot into the space would have required a second experimenter for all trials and could also support participant notions of robot capabilities that did not exist. The experiment objective and procedure were then explained to the participant(s). The participants were made aware of a small camera mounted on the ceiling above the table and of the sensors on the robot. No information was provided on how the robot would be controlled. When the participants understood the experiment and the jigsaw puzzle task, and they had completed the required consent forms, the experimenter left the room and the experiment began.

Using vision from the ceiling-mounted camera, the experimenter teleoperated the robot so it travelled around the periphery of the space in a counter-clockwise direction when viewed from above for an entire circuit, continued around the periphery to the first of the pre-randomised approach locations, and then approached radially. When the robot finished its approach to the group (as described in Section 3.5), 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 of the space from where it had approached the group. The robot did not explicitly wait for the participants to answer the questionnaire before returning to the periphery. From the position where the robot had just approached the group, it travelled another circuit of the periphery before continuing to the next approach location. This process was repeated until the robot had approached the group from all eight locations. After the last robot approach, the robot travelled counter-clockwise around the periphery of the space, returning to its starting location. The experiment was then complete, and the experimenter returned to the space with a post-experiment questionnaire for each participant to complete.
Table 1: Results from the NASA-TLX questionnaire showing number of participants from a total of 140 against scores rounded to the nearest integer.

<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>27</td>
<td>36</td>
<td>33</td>
<td>30</td>
<td>14</td>
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<tr>
<td>High Mental Demand</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Low Effort</td>
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<td>39</td>
<td>42</td>
<td>34</td>
<td>7</td>
</tr>
<tr>
<td>High Effort</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

3.8 Measurements

Measurements 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 3.5), 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.

The post-experiment questionnaire was a composite of the NASA Task Load Index (TLX) questionnaire (6 questions; Hart & Staveland, 1988), the Godspeed questionnaire (24 questions; Bartneck, Kulić, Croft, & Zoghbi, 2009), together with 4 qualitative questions on the robot approach directions and 12 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. Analysis of the data from these demographic questions is not presented here.

4. Data analysis

As all participants are different, they will experience a given event with differing levels of comfort, so the self-reported participant comfort scores cannot be used as absolute measures. Participant comfort scores were therefore converted to ranks from one (most comfortable) to eight (least comfortable). Robot approach directions that had equal participant comfort scores were assigned the same rank, and the next comfort score was assigned a rank equal to the cardinality of already-ranked scores plus one. Rank data for groups were formed by adding the two individual comfort scores before conversion to ranks. Generating group rank data this way assumes that the comfort of each participant is of equal importance in the interaction. This sequence of group rank data generation is chosen to maintain intra-participant consistency of comfort scores.

Once participant responses were converted into ranks, non-parametric statistical methods (Siegel, 1956) were required for data analysis. The major difference between non-parametric and parametric methods is that the former make no assumptions about the underlying distribution.

The Kruskal-Wallis ANOVA test (Siegel, 1956), Mann-Whitney U test (Sheskin, 2003) and an extended Watson’s U^2 test (Maag, 1966; Brown, 1994)—the directional equivalent of the Mann-
Table 2: Chi-squared results for a Kruskal-Wallis ANOVA test for the seven different seating locations. For each test, 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 Configuration O (left), which was subsequently 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 (right)</td>
<td>9.81</td>
<td>0.20</td>
<td>0.06</td>
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<td>O (left)</td>
<td>16.96</td>
<td>0.02</td>
<td>0.11</td>
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<td>L (right)</td>
<td>3.15</td>
<td>0.87</td>
<td>0.02</td>
</tr>
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<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>
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<tr>
<td>S</td>
<td>2.71</td>
<td>0.91</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Whitney U test—were used with a post-hoc false discovery rate (FDR) correction factor ($q = 0.05$) defined by Benjamini and Hochberg (1995) to verify the randomness of robot approach directions (Section 5.3) and to validate the combining of the two sets of individual data in Configuration O into one superset (Section 5.4). Rayleigh’s test of uniformity of a circular distribution (Mardia, 1972) was used to measure the uniformity of rank distributions. Rayleigh’s test was modified to account for coarse angular resolution (Stuart & Ord, 1994) and to improve error bounds—from $O(n^{-1})$ (Cox & Hinkley, 1974) to $O(n^{-2})$ (Jupp, 2001)—when mapping the vector sample mean value $R$ to the $\chi^2$ value used to obtain a p-value. A significance level $\alpha$ of 0.10 was used for the Rayleigh test. A value of 0.10 was selected rather than the more usual 0.05 since this was an exploratory study and the consequences of a Type I error are relatively minor.

Each rank distribution is the distribution of that particular rank across all eight robot approach directions. The relative orientations of the robot approach paths can therefore be exploited in a circular statistical analysis of the data. Linear statistical methods do not consider these relative orientations and consequently must refactor this information post-analysis.

5. Results

5.1 Participant demographics

In total, 140 participants were recruited, sufficient for 20 trials of each experimental seating configuration. Participants consisted of 61 males and 79 females. The mean participant age was 24.7 years with a standard deviation of 8.7 years. The minimum age was 18, and the maximum age was 73. Of the 140 participants, 114 (81.4%) expressed a belief via the post-experiment questionnaire that the robot was automated and not controlled by a person.

5.2 Task loading

The participant-reported mental demand and effort required to complete the jigsaw puzzle task are shown in Table 1. The data suggest that participants exerted a moderate amount of effort and that the task was moderately mentally demanding. These results suggest that the subjects engaged with the task as intended.
Table 3: The Mann-Whitney U test results for relative approach directions and Watson’s $U^2$ test results for relative rank distributions for the two different seating positions of Configuration O. Although $p < 0.05$ in some results, the null hypothesis was verified in all cases when the correction factor was applied.

(a) Mann-Whitney U test results.

<table>
<thead>
<tr>
<th>Dir.</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>
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</thead>
<tbody>
<tr>
<td>$p$</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>
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</table>

(b) Watson’s $U^2$ test results.

<table>
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<th>Rank</th>
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<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td>$p$</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>
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</table>

5.3 Randomness of approach direction order

It is possible that participant comfort responses will trend toward a comfort extreme as the experiment progresses, introducing a bias into the data. To minimise any such bias, the order of robot approach directions was randomised; the effectiveness of this precaution is evaluated here.

To ensure that any such bias is independent of the robot approach directions, it is required that the distribution of ordinal occurrences for each robot approach direction is the same. We form ordinal-occupancy distributions for each robot approach direction using the set of proposed orders of approach for all experiments. The null hypothesis that these eight distributions were sampled from the same underlying distribution was not rejected by the Mann-Whitney U test ($\chi^2(7, 56) = 0.01, p = 1.00, \eta^2 = 0.00$). As each experiment has one of each approach direction, and the ordinal-occupancy distributions come from the same underlying distribution, the underlying distribution must be uniform.

As each robot approach direction is equally likely to occur at any robot approach event across all experiments, a comfort rank distribution can be formed for each of the eight robot approach events. A null hypothesis that there is no comfort trend across the duration of an experiment trial is proposed. Since comfort varies across seating positions (Ball et al., 2015a), comfort rank distributions were formed for each seating position, producing a total of 56 distributions. A Kruskal-Wallis ANOVA test was performed for each seating configuration, with results shown in Table 2. The only result requiring a post-hoc multiple comparison test ($p < 0.05$) with FDR correction was the left position in Configuration O, which showed no significant differences. These results do not invalidate the null hypothesis and show that there was no trend of participant comfort responses over the duration of a trial.

5.4 Individual data of Configuration O: Persons sitting opposite each other

In Configuration O, the relative location of the other person is the same for both participants. This provides the opportunity to combine the two data sets, doubling the amount of data available for analysing individual responses. Combining the data is only valid if they are statistically not different. To check for this, a comparison test was performed for the relative robot approach directions and relative rank distributions.

The Mann-Whitney U test was used to compare the distributions for the matching relative approach directions, and Watson’s $U^2$ test for the matching rank distributions between the two data
sets. Results for these two tests can be seen in Table 3. As multiple tests were being performed the FDR correction factor was applied. There were no significant differences between matching robot approach directions or matching rank distributions, indicating considerable similarity between the two data sets and validating their union into a superset.

5.5 Determining non-uniformity and mean angles of a directional distribution

The Rayleigh test provides a p-value estimating the probability that a circular rank distribution is uniform. Table 4a shows the resulting p-values for each rank distribution of each seating position. If a rank distribution has a high probability of being non-uniform (p < 0.10), then the mean angle of the distribution, together with the rank number, can be used to determine whether the direction corresponding to the mean angle should be favoured or avoided for a robot approach.

Although a mean angle can always be calculated for directional distributions that have a non-zero vector sample mean, the mean angle only has significance when a distribution is significantly

<table>
<thead>
<tr>
<th>Rank</th>
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<th>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>
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<td>0.35 0.07 0.08 0.08 0.70 0.36 0.30 0.03 0.01</td>
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<tr>
<td>4</td>
<td>0.06 0.58 0.48 0.94 0.27 0.27 0.42 0.90 0.84</td>
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<tr>
<td>5</td>
<td>0.56 0.36 0.41 0.48 0.60 0.99 0.21 0.49 0.17</td>
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<tr>
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(b) Mean angles for the rank distributions of all group and individual seating positions.

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<tr>
<th>Rank</th>
<th>Configuration</th>
<th>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>
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<td>2</td>
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<tr>
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</table>
Ball et al., How Should a Robot Approach Two People?

Figure 4. Mean angle for distributions of Rank 2 and 8 for the individual data of Configuration O. The individual data were formed by rotating the data of the unmarked seating position to the same orientation as the marked seating position, resulting in twice as much data for the individual analysis.

non-uniform. The mean angles for all rank distributions are shown in Table 4b for completeness, but these results must be interpreted in the context of the $p$-values in Table 4a.

It is also possible for a non-uniform distribution to ‘pass’ the Rayleigh test of uniformity (e.g. a bimodal distribution with peaks $180^\circ$ apart). A visual inspection of the distributions will easily identify these cases.

5.6 Configuration O: Persons sitting opposite each other

For the individuals in Configuration O, Ranks 2 and 8 are non-uniform (column “O Ind.” of Table 4a). It is interesting to note that the distribution for Rank 2 has a higher probability of being non-uniform than does the distribution for Rank 1. Inspection shows that the Rank 1 distribution has negative kurtosis with a stronger weighting towards the ‘frontal’ approach directions 7, 8, and 1. Of

Figure 5. Circular distribution of Rank 4 in the group data of Configuration O. Each dot represents one data point. The thick radial line represents the mean angle of the distribution.
Table 5: Count of participant responses as a percentage for each robot approach direction for the rank distribution associated with the listed figures.

<table>
<thead>
<tr>
<th>Dir</th>
<th>Fig. 5</th>
<th>Fig. 6</th>
<th>Fig. 8</th>
<th>Fig. 10</th>
<th>Fig. 13</th>
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<td>22</td>
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</tbody>
</table>

the 40 participants in Configuration O, 19 scored three or more of the approach directions as being equally most comfortable. With approximately half of the participants providing three or more data points for this distribution, these data points must be spread. Steele and Chaseling (2006) showed for several statistical methods that to achieve a power greater than 0.8 when distinguishing a statistical difference between a uniform and platykurtic distribution, more than 150 sampled data points are required. With 119 data points and a $p$-value of 0.13, although the Rayleigh test classifies the Rank 1 distribution as not non-uniform, a Type II error is possible.

Fig. 4 depicts the mean angles of rank distributions 2 and 8 from Table 4b (O Ind.), showing that people seated in this configuration are more comfortable when approached from a ‘frontal’ direction and least comfortable with robot approaches from behind them. By rotating the results by 180° and superimposing them onto the non-rotated results—to account for both seating positions in Configuration O—the mean angles of the ‘comfortable’ distributions for one seating position overlap the mean angles of the ‘uncomfortable’ distributions for the seating position opposite. The best direction from which to approach a pair in this configuration is therefore from either side (direction 2 or 6 in Fig. 2b), minimising the maximal discomfort likely to be experienced by either person.

For the group results of Configuration O, the most non-uniform rank distributions are those of Ranks 4 and 8 (Table 4a, column O). As Rank 8 was highly non-uniform and unimodal in the individual analysis, rotating half of the data to generate the group result still provides a non-uniform bimodal distribution with peaks at robot approach directions 4 and 8. The distribution for rank 4 is asymmetric (Fig. 5), and interestingly has no data for approach directions that are directly in front of, or behind the participant.

Column 2 of Table 5 provides the count of participant responses as a percentage for each robot approach direction of the Rank 4 distribution for the group data of Configuration O. The remaining columns provide such information for the referenced figures.

5.7 Configuration L: Persons sitting in L-shape

For the left seating position in Configuration L, the distribution for Rank 1 (Fig. 6) was non-uniform (column L (L) of Table 4a) with a mean angle (column L (L) of Table 4b) directly in front of the seating position. With the majority of the distribution being sampled from directions 1 to 3, this distribution has negative kurtosis, similar to the Rank 1 distribution of the individual data in Configuration O. It is interesting to note that while the mean angle of the Rank 1 distribution is essentially directly in front of the seating location, the front-angled robot approach directions (directions 1 and 3 in Fig. 6) were assigned this rank more often. This result supports the result in Dautenhahn et
al. (2006) that robot approach directions from a front-left or front-right direction are preferred to a direct front-on approach. The distribution for Rank 8 is unimodal and non-uniform, with a mean angle located directly behind the subject’s seating position. The distribution for Rank 7 is more spread, with most of the data points from directions 3 and 4, giving a mean angle of $-168^\circ$ towards the back-right of the seating position. Fig. 7 shows the relative orientation of the mean angles for this seating position. All rank distributions were uniform for the seating position on the right of Configuration L.

The distributions for Ranks 2 and 3 in the group results for Configuration L are non-uniform, as shown by column L of Table 4a. Both are unimodal, with the data of Rank 2 clustered around directions 1 and 2, and the data of Rank 3 weighted around directions 6, 7, and 8. The data of Rank 1 (Fig. 8) are mostly spread across directions 7, 8, ..., 3, 4. Similar to Rank 1 for the individual data of Configuration O, while the distribution is not non-uniform according to the Rayleigh test, a Type II error is possible.
The results show that if two people are seated similarly to those in Configuration L, then a robot should approach from between directions 1 and 2, as defined in Fig. 2b.

5.8 Configuration A: Persons sitting adjacent

Rank distributions 1, 2, 3, 6, 7, and 8 for the seating position on the right of Configuration A are all non-uniform, as shown by column A of Table 4a. The orientations of mean angles for these rank distributions relative to the subject can be seen in Fig. 9b. The ‘more comfortable’ ranks have mean angles in the front-left region, where the robot is visible to both participants, is as far as possible from the seating location and has the table between the robot approach position and the seating location. The most ‘uncomfortable’ rank distributions have mean angles that are in the rear-right region with respect to the participant. In this region the robot is not directly visible and can also approach quite close to the seating position.

Although not as pronounced, a similar trend is present for the seating position on the left of Configuration A; see column A (L) of Table 4a. The distribution for Rank 1 is bimodal (Fig. 10) with one peak towards robot approach direction 8 and the second peak at direction 3. As for the ‘more comfortable’ rank distributions for the right position of this configuration, the Rank 1 mean angle corresponds to an area where the robot is visible to both participants but is still physically removed, with the table between the location of the seating position and where the robot would approach from. The mean angle for the Rank 8 distribution is again towards a region where the robot is not directly visible to the subject and can approach close to their seating position.

Unsurprisingly, the group results for Configuration A are similar to those of the Configuration A individuals, as they have the same orientation. The mean angles for the ‘more comfortable’ distributions, Ranks 1 and 2, are in front of the group, while the mean angles for the ‘least comfortable’ rank distributions, Ranks 6, 7, and 8, are behind both seating positions (Fig. 11). Given the mean angles associated to the most and least comfortable rank distributions, the best direction to approach a pair of people in Configuration A is from the ‘frontal’ region. A robot approach from this region is visible by both people and aligns with the mean angle for the most comfortable rank distributions of each person. Similarly, the ‘rear’ region, associated with the mean angles for the most uncomfortable rank distributions, should not be used to approach people in this configuration.
Figure 9. Mean angles for the significantly non-uniform rank distributions of both the left and right seating positions in Configuration A. The seating position in each figure that corresponds to the mean angles is denoted by a dot.

Figure 10. Circular distribution of Rank 1 for the left position of Configuration A, represented by the marked chair. Each dot represents a data point.
5.9 Single person

The three ‘most comfortable’ and ‘least comfortable’ ranks have non-uniform distributions (Table 4a, column S) for the configuration where only one person was present. The mean angles for these non-uniform rank distributions can be seen in Fig. 12. The distributions for Ranks 1, 2, and 3 are all highly non-uniform, as there are either very few or no sampled data points associated with the ‘rear’ approach directions 3, 4, and 5.

The distribution for Rank 8 is heavily weighted to directly behind the seating location (direction 4), and the distributions for Ranks 6 and 7 are bimodal with peaks at both robot approach directions 3 and 4. This results in all of these distributions having mean angles that are directly behind the seating location.

The large spread of data for the ‘more comfortable’ rank distributions show that, although a single person should be approached from the ‘frontal’ region, there is tolerance in the relative angle of approach. Similarly to the previous configurations, the robot should avoid approaching from behind the person to maximise comfort.
6. Discussion

In the previous section, the Rayleigh test for uniformity was used to determine which comfort rank distributions were statistically non-uniform for different seating positions across a variety of configurations. The mean angles for the statistically non-uniform configurations were calculated and used with the rank of the distribution to determine whether or not a robot should approach a pair of people from the direction associated with the mean angle. The mean angles for the more comfortable ranks were typically used to define directions that a robot should approach a group from, as this would maximise the comfort of a person. The sole exception to this was in Configuration O, when the two seating positions were opposite each other, and the mean angle for a comfortable rank of one person overlaps with the mean angle of an uncomfortable rank for the other person. In this configuration, we conclude that the robot should approach the group from a side direction, thereby minimising the maximum discomfort experienced by the group. In all four configurations, the direction that the robot should approach the group from is (a) located in the largest unoccupied zone in the p-space, (b) in a direction where the robot is visible to both participants, and (c) in a direction where the robot maintains a maximal distance from both participants.

The results for Configuration S agree with the prior results of Dautenhahn et al. (2006) and Walters et al. (2007), with the most comfortable directions of robot approach being in front of the person. While the similarity of results is unsurprising, it does validate our methodology for the single-person experiment and, by extension, the experiments with pairs of people. Fig. 13 show the distribution of Rank 1 for the single-person configuration. The distribution of this most comfortable rank suggests an angular tolerance for where the robot can approach from and also provides evidence contrary to the claim of Dautenhahn et al. (2006) that approaches from the front-diagonal directions (directions 7 and 1) are more comfortable. This can be explained by the fact that it is possible in this work for participants to mark several directions as equally comfortable, while Dautenhahn et al. (2006) require an explicitly preferred direction of approach. Our findings are similar to those of Karreman et al. (2014). Both works found that a robot should approach groups from frontal directions.

A potential concern of this experiment is that participants may focus on the movements of the robot as it traverses the periphery of the space and try to guess the next robot approach direction. With participants putting a moderate amount of cognitive effort into solving the jigsaw puzzle task.
(Table 1), we believe that this participant behaviour did not occur during the experiments. Should the behaviour have occurred, it would be expected that participant guesses of the next robot approach direction would increase in accuracy over the course of the experiment. The analysis of ordinal data in Section 4 shows no change in participant comfort responses as the experiment trials were conducted. This suggests that if this behaviour did occur, it did not influence participant comfort results.

7. Conclusion

An experiment was conducted in which a total of 140 people seated in pairs, and individually, were approached from eight different directions by a robot of mechanical appearance. The participants scored their comfort level with each approach of the robot.

The Rayleigh test of uniformity was used to identify statistically non-uniform comfort rank distributions. The mean angles and comfort ranks associated with the non-uniform distributions were used to assess the directions of robot approach that were deemed to be most and least comfortable by participants.

It was found that a robot should approach pairs of people from a direction that allows good sight of the robot by both people and is centred on the largest unoccupied area of the pair’s p-space.

When participants are seated opposite each other (Configuration O), the most comfortable direction of robot approach for one person coincides with the least comfortable direction of approach for the other. In configurations like these, the robot should approach from a direction that minimises the maximum discomfort of either person. Experiments showed that the general principle of minimising the maximum discomfort extends to the other group configurations.

One of the difficulties with this experiment was that it had to be performed in a highly controlled and particular manner, such that data could repeatedly be obtained from particular seating configurations. Interesting future challenges to explore include the extension of this work to consider how a robot should approach pairs of people for all seating configurations and consideration of how the environment influences which approach path a robot should take.

References


Robot Interaction (pp. 317–324). doi:10.1145/1228716.1228759


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