Personal Space Intrusion in Human-Robot Collaboration

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ABSTRACT
Our research aims toward a method of evaluating how invasion of personal space by a robot, with appropriate context, affects human comfort. Work has been done to define comfortable social distances between humans and robots using the stop distance technique. But we aim toward filling an apparent gap in human-robot proxemics research: the results of physical interaction within that social distance. This paper describes our implementation of a testbed to evaluate how comfort changes as a result of invasion of personal space by a robot during a collaborative task with a shared workspace. The study we have designed and piloted causes the robot to reach into the human's personal space at different distances and urgency levels. We have also identified some ways in which further exploration in this area can be done.

Author Keywords
Human-robot proxemics; collaboration; personal space; comfort.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Personal space has been defined in research as "the area individuals maintain around themselves into which others cannot intrude without arousing discomfort" [14]. Consequently, maintaining appropriate interpersonal distance is important in social interactions. However, there are many scenarios in which interaction within personal space may be appropriate or necessary, for example, in healthcare, in the home, or in the workplace.

There are several real-world scenarios in which human comfort during close interaction with robots is already important and applicable. Research has shown that robot-assisted movement training may prove more effective than conventional methods following a stroke [22]. However, it will be imperative that patients are reasonably comfortable when the robot is inside their personal space.

As humans, we are implicitly taught to maintain appropriate social distance as a side effect of the culture we grow up in; it is rarely something we do consciously. We will only encroach on someone's personal space when it is appropriate, and when we do so we are aware of our actions and both parties use proxemic behaviours to establish comfort, as described in the Argyle-Dean equilibrium theory [17]. But how can a robot's behaviour be designed so that it will only intrude on someone's personal space in a manner that is considered socially appropriate? This is important in designing social behaviour for humanoid robots who will interact closely with humans.

There are many factors which might influence comfort during personal space invasion by a robot, including movement speed, the robot's appearance, facial expression, and more [17, 27]. We have selected two factors with which to explore the problem. More specifically, we aimed to find a method of answering the following research question:

When a human's personal space is violated by a robot during collaboration on some task, how is the human's comfort affected by different levels of portrayed urgency and depths of intrusion?

RELATED WORK
There is an apparent gap in research done in human-robot proxemics; we have found nothing that attempts to answer our question. Some relevant work has been done in the related area of human-robot trust [1, 2, 20, 23, 25]. Some of this research has been about trusting a robot's ability to correctly perform its function [1, 2] and other research has covered the concept of trust and personal investment [25]. This is relevant to our question because we consider trust to be a contributing factor to comfort.

Some additional related topics are discussed in the following subsections. Our research is based closely on the findings from the studies described here.

Personal Space
Edward Hall's theory of proxemics [11] is widely cited in both human-human and human-robot proxemics research. In

Figure 1. Participants interact with Baxter on a collaborative Lego-building task during our pilot study.

summary, this theory is the notion that we are at the centre of several nested circles that define the boundaries of our intimate space, personal space, social space, and public space. Hall deemed the boundary of personal space to be a circle with radius 1.2 m around a person.

In [17], Argyle and Dean present research which has become widely known in the social sciences as the Argyle-Dean equilibrium theory. This theory states that personal space is defined through the establishment of an equilibrium between four factors: amount of eye contact, interaction distance, intimacy of topics discussed, and amount of smiling. According to this theory, each of the four factors is subject to approach and avoidance forces. People will make behavioural compensations to reach equilibrium when one of the four factors is out of balance. For example, if two people are discussing an intimate topic, they will be likely to interact at a closer distance than normal. If an imbalance in the equilibrium is in the direction of too much intimacy, the authors state that anxiety will increase.

These two theories are important to note because they highlight the central difference between our research and previous work that relied heavily on Hall's theory: personal space is not a fixed boundary and there are ways to interact inside it that can maintain a comfortable equilibrium.

Research by Buchanan et. al. [8] has done some investigation into the invasion of personal space. Their experiment was performed in an elevator containing two floor-selection panels. Subjects had to choose which panel to use to select their floor while experimenters stood next to each of the two panels. All 93 participants chose to violate personal space rather than take an alternate approach such as asking the experimenter to select a floor for them. This shows us that given a sufficient cause for invading personal space, the action may be socially appropriate and worth investigating human-robot interaction.

Human-Robot Proxemics

Previous research in human-robot proxemics has stopped at the perceived border of personal space using the stop-distance technique. This is a technique where a robot will approach a human (or vice versa) until the closest distance is achieved at which the human still feels comfortable, at which point they will say "stop".

In [18], Walters et. al. performed a six-week long study of human-robot proxemics. Participants were given a remote control and were instructed to move the robot to a comfortable social distance. They also had to approach the robot until they reached a comfortable social distance. That distance was recorded by the robot. The results of this study found that participants on average were willing to approach the robot to a point 5 cm closer than they would allow the robot to approach them. They also found that after the second week, there was no significant change in approach distances in the repeated sessions. The stop-distance recorded by the robot was deemed to be the boundary of each participant's personal space.

In [27], a search-and-rescue scenario is described in which the intent was to suggest methods of evaluating the proxemic behaviour of robots. This paper describes the creation of a robot that is capable of determining a person's location and which has various adjustable behaviours. The purpose was to provide a testbed that, if used by others, would allow for comparable results between human-robot proxemic studies. Although the emotional consequences of personal space intrusion by a robot were not the intent of this paper, it does mention in passing that stress levels rose when a robot approached closer than the participants' personal space boundary.

Other research has shown that people prefer a robot's behaviour to be scaled as it approaches the personal space boundary [27], and that people are often willing to stand closer to a robot than to another person, likely because the robot is seen as a machine rather than a social entity [24].

This subsection serves to show how our research question differs from previous research in this area. Rather than measuring the distance at which a robot should stop approaching a human, we are defining a context for the invasion of personal space: a collaborative task that requires a human and a robot to interact inside the comfortable “stop” distance described in [18].

OUR SOLUTION DESIGN

We began modelling the human-robot study design using human-human trials. This helped to gain insights into how the human-robot study would be conducted, as well as give us some preliminary insights into how different reaching behaviours achieve different reactions.

The Human-Human Pilot

Using a generic Lego kit and a set of instructions to build a small Lego train, we conducted a human-human version of the pilot we had in mind. We had a participant build the Lego train while another participant, acting as the robot and supplier of Lego pieces, dumped Lego pieces from a measuring cup at various distances and speeds around the building participant. We required the builder to use only one hand in order to simulate the human-robot pilot we had in mind in which a galvanic skin response sensor and heart rate monitor would be attached to their other hand. This is described further in the following subsection.

We performed one trial-run of this new study and observed that the human paused their task briefly and leaned away slightly when the other person was physically in the way of them completing their task (Figure 2). There was no observable reaction when the person entered their personal space but was not in their way.

The Proposed Human-Robot Study

Using the insights gained from previous work and our human-human pilot, we have designed a study protocol that can be used to evaluate how human comfort is affected by three different depths of intrusion into personal space and two different levels of portrayed urgency of the intrusion during a collaborative task with a robot. These are just two of many factors which could influence comfort during personal space invasion by a robot [17, 27].

We chose to use the Xiaomi Mi Band 2 for measuring heart rate and the Mindfield Biosystems eSense Skin Response monitor to measure galvanic skin response (GSR). Both of

Figure 2. The builder is waiting for the supplier to deposit the Lego blocks before continuing to build.

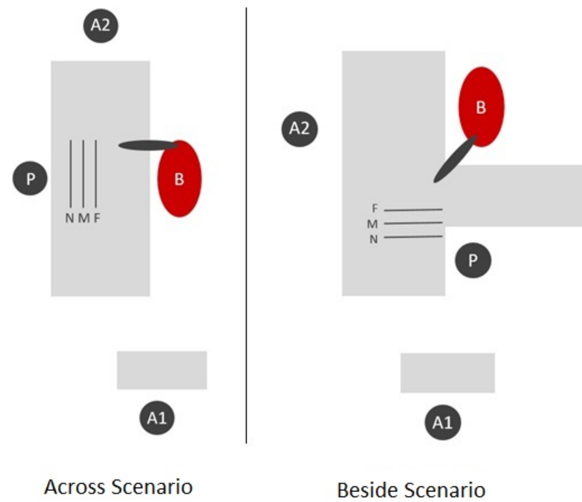

Figure 3. The positions of Baxter (B), the participant (P), and administrators A1 and A2 in both scenarios. N, M, and F represent not-to-scale indications of the near, medium, and far reach distances respectively.

these measurements have been suggested in previous related work as methods of measuring stress [13, 14, 19]. Physical stress has been given as the definition of discomfort in personal space research [14], which is why we have chosen to measure it. We considered it important that the measurements be taken in a way that was as non-invasive as possible in order to achieve accurate measurements of stress produced by interacting with the robot, rather than stress produced by intrusive measurement techniques.

We chose to use the Godspeed questionnaire [3] paired with another questionnaire called the Robotic Social Attributes Scale (RoSAS) [5], which was designed to counteract the weaknesses of Godspeed [6]. RoSAS includes items intended to measure discomfort.

Details

The robot we used for this design was Baxter (Figure 1), a research robot made by Rethink Robotics. It is a large, humanoid robot with an LCD screen mounted on the head, used here as a face, and two arms with seven degrees of freedom each.

Our study design requires two administrators, referred to here as A1 and A2. A1 controls Baxter during the study through a Wizard of Oz implementation and records the participants’ heart rate, while A2 supplies Baxter with appropriate Lego pieces to deliver to the builder. The presence of A2 is required in order for A1 not to miss heart rate recordings.

We designed two versions of the study (Figure 3) in order to accommodate a scenario in which the builder is seated across the table from Baxter (Across Scenario) and a scenario in which the builder is seated next to Baxter on the

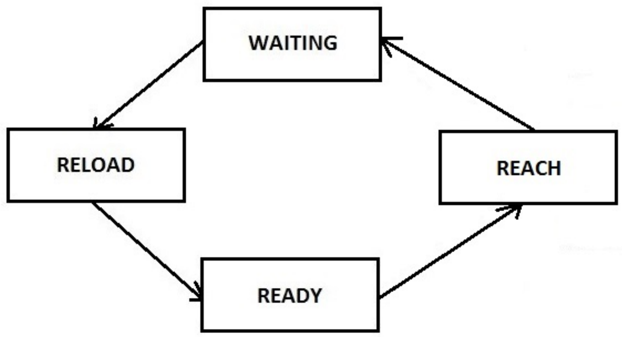

Figure 4. State transition diagram for the study.

same side of the table (Beside Scenario). Half the participants of a study performed according to this protocol should start with the Across Scenario while the other half should start with the Beside Scenario. This is to attempt to avoid confounding as a result of the order in which the scenarios are presented.

Baxter's movements for both scenarios occur according to the state transition diagram shown here (Figure 4). The transitions between each state are initiated by user input from A1.

Baxter starts each scenario in the waiting state with both arms resting just above the table and a cup attached to one gripper. From here, Baxter moves to the reload state, in which the reaching arm moves toward A2 to retrieve the Lego pieces. Baxter's gaze also moves away from the participant and toward A2 during this state. Before entering one of the six reach states, Baxter moves to the ready state briefly, which is the same position as the waiting state except the cup now contains Lego. Then Baxter's arm reaches toward the participant, dumps the Lego from the cup, and retracts back to the waiting state.

In the Across Scenario, the participant is seated across the table from Baxter. Each of Baxter's reach states cause him to reach forward toward the participant, encroaching on their personal space at three different distances and two different levels of urgency. The Beside Scenario is similar, except the participant is located to Baxter's left. The different reach states cause Baxter to reach toward the left with his left arm at three different distances and two different levels of urgency.

The two urgency levels are defined by the amount of time it takes Baxter to complete the dump. In the "fast" states, Baxter dumps the Lego as soon as the arm arrives at the reach distance. This results in Baxter's arm remaining within the builder's personal space for a shorter period of time. In the "slow" states, Baxter waits for 1.5 seconds before dumping the Lego and before returning to the waiting state. In these states, Baxter's arm stays inside the builder's personal space for a longer time.

In both scenarios, the different reach distances are two inches apart. This is a somewhat arbitrary distance chosen to make the difference in depth of personal space intrusion subtle yet noticeable. In the Across Scenario, the near distance is 6 inches from the participant's edge of the table. This distance was chosen based on a combination of the width of the table we used (24 inches) and the length of Baxter's arms. The medium distance is 8 inches, and the far distance is 10 inches. In the Beside Scenario, we measured from the participant's edge of the table separating the participant and Baxter, which has a width of 20 inches. The near distance is two inches closer to the participant than the edge of the separating table, the medium distance is at the edge of the separating table, and the far distance is two inches closer to Baxter.

In order to account for the possibility that the participant will become accustomed to Baxter reaching into their space, and therefore become more comfortable with each reach, the reaches are initialized in a pseudo-random order decided by a Latin Square (Tables 1 and 2). Each of the six reach states, defined by the reach distance and urgency level, are repeated six times in order to obtain sufficient data, resulting in 36 reaches in total for each participant. Each of the two scenarios will take between 20 and 25 minutes to complete for each participant.

Reach	Code
Far-Fast	1
Far-Slow	2
Medium-Fast	3
Medium-Slow	4
Near-Fast	5
Near-Slow	6

Table 1. Codes for reach states.

Participant	Sequence
P1	1, 2, 6, 3, 5, 4, 2, 3, 1, 4, 6, 5, 6, 1, 5, 2, 4, 3, 3, 4, 2, 5, 1, 6, 5, 6, 4, 1, 3, 2, 4, 5, 3, 6, 2, 1
P2	2, 3, 1, 4, 6, 5, 3, 4, 2, 5, 1, 6, 1, 2, 6, 3, 5, 4, 4, 5, 3, 6, 2, 1, 6, 1, 5, 2, 4, 3, 5, 6, 4, 1, 3, 2
P3	3, 4, 2, 5, 1, 6, 4, 5, 3, 6, 2, 1, 2, 3, 1, 4, 6, 5, 5, 6, 4, 1, 3, 2, 1, 2, 6, 3, 5, 4, 6, 1, 5, 2, 4, 3

Table 2. Reach sequences used for each participant.

The LCD screen on the robot displays a face similar to the one seen in Figure 3. Baxter gazes down toward the table where the participant is building and blinks or glances up toward the participant randomly throughout the interaction. Our use of the neutral facial expression rather than a blank

Figure 5. Left: interaction during the Beside Scenario; right: interaction during the Across Scenario.

screen or some other image is merely to increase Baxter's presence as a social entity. We also hope that by using a neutral face, we can avoid the effect of emotional facial expressions on the results.

Protocol

A1 introduces the study to the participant by saying the following: "We are studying collaborative human-robot interaction. Your task is to build a house. The more elaborate and creative your house can be, the better. Feel free to use or not use any pieces you are given. Keep building until we stop you. Baxter will act as your assistant and will decide when to provide you with more Lego pieces throughout the process. We will be measuring your heart rate and skin response during the collaboration, so you will need to build the structure with one hand while the sensors are attached to your other hand. If at any time you wish to stop the study and withdraw your participation, you may say so and any data we've gathered from you will not be included in our results."

Before the study begins, the participant will put on the heart rate monitor and GSR sensor. These sensors are used on the participant's non-dominant limb. They will use only their dominant hand to build the Lego structure.

The first scenario for the study is then conducted. Participants build the Lego structure while Baxter, who is secretly controlled by A1, reaches toward A2 to receive Lego blocks and then enters one of the six reach states to deliver the blocks to the participant.

After the participant has completed the first scenario, A1 introduces the second scenario by saying the following: "This time, your task is to build a vehicle. The more elaborate and creative your vehicle can be, the better. Feel free to use or not use any pieces you are given. Keep building until we stop you."

The second scenario is then conducted. After both scenarios are complete, the participant fills out the Godspeed and RoSAS questionnaires. Note that the order in which these descriptions are given should be adjusted according to which scenario is being performed first.

Finally, A1 debriefs the participant about the study by saying: "We are doing this study to measure stress as it relates to invasion of personal space by a robot's reach during collaboration. We will be comparing your heart rate measurement and skin response based on Baxter's different reach distances and urgency levels."

DISCUSSION

We ran a pilot to test our study design using three participants (P1, P2 and P3). Videos of each session were recorded with audio so that we could more easily make observations about stress-related behaviours during the study.

Consistent with the Argyle-Dean equilibrium theory described previously, we were able to observe compensatory behaviours when the builder's personal space was invaded. In some situations, especially when Baxter's reach was closer to the builder, we were able to observe the builder leaning away from Baxter. Similarly, P2 seemed to lean away from Baxter throughout most of the interaction, reaching toward Baxter to catch the Lego blocks. In these moments, P2 and Baxter were mutually reaching toward the middle. We were also able to observe a few of the stress-related behaviours described in [12], such as giggling and lack of eye contact. However, since the participants were focused on the Lego in front of them, not on Baxter, we don't consider the lack of eye contact in this study to be necessarily indicative of stress.

Unfortunately, during this pilot, the mobile app associated with the eSense monitor only recorded partial data for each participant. Because of this, we are leaving the GSR data out of our discussion of the preliminary results.

Three heart rate measurements were taken during each reach: one as Baxter begins reaching, one when Baxter reaches the specified distance, and one as Baxter is retracting his arm. We recorded the increase in heart rate during each of the six reach states, averaged over six repetitions of the reach.

We do not have enough data to draw meaningful conclusions from the recorded heart rate information. A full study with a larger number of participants is required in order to determine whether there is a correlation between stress, heart rate, and invasion of personal space by robots. However, we were able to observe some consistencies between recorded heart rate data and the questionnaire responses described below.

Responses to similar items in the Godspeed and RoSAS questionnaires usually had similar responses, but there were occasional inconsistencies. Since Godspeed has been shown to produce unreliable results [5, 6], we have chosen to focus our discussion on the RoSAS results. In the RoSAS questionnaire, participants were asked to rate, on a 9-point Likert scale, how associated each of the items were with Baxter based on their experience during the pilot. We expected to see higher levels of stress in participants who were less comfortable with Baxter to begin with. The items associated with discomfort were: scary, strange, awkward, dangerous, awful, and aggressive. The other items pertained to warmth and competence. The items from all three factors were mixed together and presented in a random order for each participant.

P1 gave fairly consistent low association ratings to the discomfort items, with an average of 3.17. P2 gave all discomfort items the lowest possible rating, resulting in an average of 1.00. However, P3 gave higher association ratings to the discomfort items, with the average discomfort association rating being 4.17. This is consistent with P3's greater increase in heart rate during the reaches compared to P2 (2.36 bmp versus 1.08 bpm). However, more data from a greater number of participants is required to determine if this consistency has true significance to our research question. From a preliminary standpoint, it does suggest that via this testbed we may be able to confirm our hypothesis that higher stress levels are seen in individuals with a higher level of discomfort around robots.

We also took note of a comment from one participant who suggested that Baxter should smile. For this study, we supplied Baxter with a neutral facial expression (Figure 3). But this participant mentioned that, due to Baxter's lack of a smile, they felt they were being judged. This shows how facial expression might play a role in the results of the study, although it was not one of the factors we chose to evaluate. However, the Argyle-Dean equilibrium theory does support this idea [17].

CONCLUSION

The goal of this research was the development of a testbed to identify how collaboration involving violation of a human's personal space by a robot affects comfort levels. We hope the results of our pilot study will provide motivation for continued work in this area, and in turn provide insights into how humanoid robots should behave in social situations, particularly during collaborative tasks or perhaps even more intimate interactions such as healthcare.

Previous research in human-robot proxemics seems to have only been done using the stop-distance method, determining the boundary of personal space between humans and robots. Our research aims to delve deeper, evaluating the emotional implications of interaction within someone's personal space.

Through our pilot, we were able to confirm that our proposed research question is valid. When participants had their personal space violated by the robot, their comfort levels seemed to be affected. We observed compensatory behaviours such as leaning in all participants, consistent with the Argyle-Dean equilibrium theory. We were also able to observe that a participant with a higher RoSAS discomfort rating also had a greater increase in heart rate during invasion of personal space than a participant with a lower discomfort rating. Further research will need to be done in order to determine how a robot's intrusive behaviour impacts stress levels and causes discomfort.

Future work in this area may include an extension of this pilot study into a full study. It may also include the testing of different movement speeds, facial expressions, amount of eye contact, alternate distances from the ones used here, or the addition of auditory conditions such as voice. Collaboration with different robots should also be considered; Baxter's large arms and body size may be more intimidating than some other robots, which may affect the results.

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