An Empirical Framework for Human-Robot Proxemics.[1]

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Abstract. An empirical framework for Human-Robot (HR) proxemics is proposed which shows how the measurement and control of interpersonal distances between a human and a robot can be potentially used by the robot to interpret, predict and manipulate proxemic behaviour for Human-Robot Interactions (HRIs). The proxemic framework provides for incorporation of inter-factor effects, and can be extended to incorporate new factors, updated values and results. The framework is critically discussed and future work proposed.

1 INTRODUCTION AND BACKGROUND

If domestic and service robots are to become truly useful, in addition to performing useful tasks they must also be socially acceptable and effective when interacting with the people who share their working environment (cf. [1], [2] & [3]). Fong et al. [4] describe socially interactive robot characteristics: To express and/or perceive emotions, communicate with high-level dialogue, learn and/or recognize models of other agents, establish and maintain social relationships, use natural cues (gaze, gestures, etc.), exhibit distinctive personality and character, and learn or develop social competencies.

Nass et al. [5] and Reeves and Nass [6] found that people have social relationships with computers including politeness, reciprocity, attribution of gender stereotypes and personality in spite of knowing that they are machines. Therefore, people will react and relate socially to robots in some of the ways that they do to humans, computers and other artefacts. Embodied non-verbal interactions, such as approach, touch, and avoidance behaviours, are fundamental to regulating human-human social interactions (cf. [7]) and the physical embodiment of robots makes it likely that they will have to exhibit appropriate non-verbal interactive behaviours. The study of how humans use and manipulate distances between each other with regard to social behaviour and perceptions is called *proxemics,* This paper focuses on empirical research into Human-Robot (HR) proxemics and proposes a framework for HR proxemic factors which will facilitate future study. Relevant findings from Human-Human proxemics, Human-Computer Interaction (HCI) and Human-Robot Interaction (HRI) research are first reviewed.

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1.1 Proxemics

Harrigan et al. [8] provide a general introduction into non-verbal human behaviour, including proxemics. Hall [10] observed that human social spatial distance varies by the degree of familiarity between interacting humans and the number of interactors. Later, Hall [11] provided a framework which categorized the main social spatial zones by interaction and situation. Hall estimated these distances visually in terms of arm lengths, close contact and threat/flight distances, but other researchers have assigned more precise numerical values [9] (Table 2). Other factors have been identified which affect human-human proxemics and there is evidence that even relatively small differences and changes in human proxemic distances (of the order of 2 cm to 15 cm) are significant. Horowitz et al. [12] found that participants were "comfortable" approaching arbitrarily close to inanimate objects. Sommer [13] stated that there were no social proxemic effects for objects and people can approach arbitrarily close without discomfort. Stratton et al. [14] found that mean "comfortable" approach distances between human participants were approximately 51cm (20in) and that significant differences in approach distance correlated with participants' notions of "self-concept" which is a trait that is related to the social status of participants. They also found that participants approached a dressed headless tailor's dummy to a mean approach distance of 55cm (22in). This was slightly (but not significantly) greater than the mean human-human approach distances. The authors suggested that participants may have taken a slightly greater approach distance due to a mild form of the "fear of the strange" effect. This was observed in animals and noted by Hebb [15], where chimpanzees were observed to keep greater distances from images of distorted chimpanzee faces and limbs than they did to non-distorted parts or other images. Kubinyi et al. [16] found a similar effect with regard to dogs and robots; adult dogs tended to leave larger distances between themselves and a "furry robot" dog than for either a toy car (the control), a real puppy or a "hard robot" dog. This effect is possibly related to the biological

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

Table 1 Human-Human Personal Space Zones (cf. Lambert [9])

origins of the "uncanny valley" effect in humans noted by Mori [17] and discussed by Brenton et al. [18] and MacDorman [19] with regard to androids (very human-like) robots.

Perceived threat can also affect proxemic distances and is possibly related to the "flight reaction" originally observed in birds by Hediger [20]. This occurs when a perceived threat rises beyond a certain level and an animal will prepare to either fight or flee according to its nature and the context of the threat. For humans and primates where the perceived threat is actually minimal (i.e. feeling uncertain rather than threatened), the response is proportional and they take up slightly greater distances from the source of the perceived potential "threat".

Gillespie and Leffler [7] concluded that much of the observed variation in social distance between *communicating* humans is accounted for by the relative status of the interactants. The higher the relative status of one interactor, the more distance relatively low status interactors will keep, whereas relatively high status individuals do not respect the social spaces of other lower status individuals. The concept of status is not a one dimensional quantity: It can be perceived in terms of a combination of factors including age, hierarchical seniority, self-concept, intelligence, charisma, physical presence, gender and force of personality.

Burgoon and Jones [21] explained many seemingly contradictory aspects of human-human proxemic behaviour by suggesting that relatively small manipulations of the distance between interactants were a social "reward and punishment" mechanism. In any interaction there would be an optimal social distance and that one or other of the interactors could then "punish" or "reward" the other interactor by making (relatively small) adjustments in an appropriate direction. For example, if a woman wanted to encourage a man's attention she may "reward" him by moving closer than might be expected or, on the other hand, literally "keep her distance". The same theory can also explain how high status interactors can "reward" lower status interactors by moving closer, but lower status interactors can "reward" higher status interactors by keeping a greater distance.

In the related field of HCI Benford et al. [22] used a spatial zone model to detect the willingness of avatars to interact with agents. Bailenson et al. [23] investigated interpersonal distances in immersive virtual environments between humans (avatars) and computers (agents). Overall, participants maintained interpersonal distances that were comparable to those for real humans (approximately 0.5m), keeping greater distances from virtual humans when approaching their fronts compared to their backs. When participants *believed* that virtual humans were avatars (even when really computer-controlled) they also tended to keep further interpersonal distances than when they believed the agents were computer controlled. The significant differences between interpersonal distances found by this study were of the order of 3 to 7 cm (approx. 1.4 to 2.8 inches).

1.2 Human-Robot Proxemics

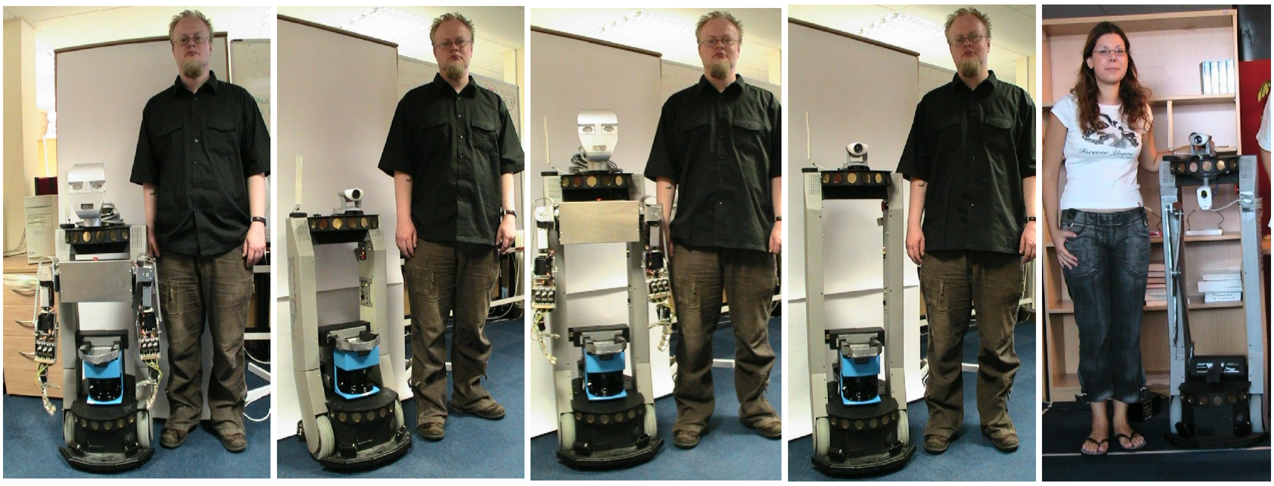
Breazeal [24] found that humans responded socially to expressive zoomorphic robots in some very fundamental non-verbal ways with regard to turn-taking in speech communication and respecting the robot's interpersonal space. Nomura et al. [25] found that both participants' negative attitudes and anxiety towards a small size humanoid robot, RobovieM (29 cm tall and 1.9 kg), had statistically significant effects on users preferred (comfortable) robot approach distances. Hűttenrauch et al. [26] concluded that in HRI user trials most participants kept interpersonal distances from the robot corresponding to Hall's Personal Spatial Zone (0.45m to 1.2m). In initial HRI proxemic trials we found that groups of children tended to approach a PeopleBot™ robot to similar distances on first encounter [27] but for individual adults approaching the same robot, the approach distances were more ambivalent and inconclusive [28][29]. In an HRI experiment with a similar mechanoid appearance robot with a simple pointing arm (Figure 1, Robot E) which used different voice styles, participants initially encountering the robot took significantly different comfortable approach distances [30]. It was suggested that these differences may be caused by a slight initial uncertainty due to the perceived inconsistency between the robot appearance and voice styles (Table 2).

Our recent main series of HRI trials run in 2006, have found factors affecting Robot to Human (RH) comfortable approach distances which are summarized here (Table 2). Participants generally allowed robots to approach more closely during physical interactions than under verbal or no interaction conditions [31]. People generally preferred more humanoid appearance robots to keep a further distance away than mechanoid robots, but the robot height (short = 1.2m, tall = 1.4m) had no effect [3]. Interestingly however, we found that participants' *preferences* for particular robot attributes did affect participants' comfortable approach distances with regard to all robot types [32]. Those who *preferred* a humanoid robot (i.e. with some human-like features, but obviously robotic) appearance (Figure 1, Robots B and D) also tended to allow whichever live robot they were interacting with to approach closer than those who *preferred* a mechanoid robot. Also, those who *preferred* a tall robot (Figure 1, Robots C and D), also tended to allow whichever live robot type they were interacting with to approach closer than those who *preferred* the short robot.

The results from our trials are summarized in Table 2 where all distances have been compensated to satisfy a standard measurement between the human and the robot's closest body trunk parts (i.e. not including arms or manipulators). These distance measurements (as best as we can tell from the published details) are also roughly comparable to those by Hall for his spatial zone distances and Stratton et al. [14]. These HRI trials were run using semi-autonomous robot control techniques in resource intensive HRI trials [33].

2 A PROVISIONAL FRAMEWORK FOR HR PROXEMICS

Table 3 shows the factors for robot appearance, preferences and interaction context and situation, which we have found experimentally to affect HR approach distances. The distance measurements are rounded to the nearest whole cm. Some values are predicted estimates from based on our earlier experimental results which indicated a relatively high degree of symmetry between similar physical situations where Humans approached Robots and Robots approached Humans for comfortable approach distances [29]. The distances are given as relative differences to the Grand Mean approach distance of 57cm. This



Robot A Robot B Robot C Robot D Robot E

Figure 1 The PeopleBot™ Robots used for the large HRI Studies: A) Short Mechanoid, B) Short Humanoid, C) Tall Mechanoid, D) Tall Humanoid. and E) the Mechanoid robot used for the robot voice style trial.

figure was gained from a previous large scale HRI trial, and was calculated over all the repeated measured preferred approach distances for all the trial conditions (for robot autonomy, interaction context, situation and approach direction). It is also close to the overall mean approach distances obtained by Stratton et al. for both humans (20in = 51cm) and the tailors dummy (22in = 56cm) used as a control [14].

Using the relative differences given in Table 3, a *default*

Approach Context	**Mean (cm)**	**Standard Error (mm)**	**95% Confidence Interval (cm)**	
			Lower Bound	*Upper Bound*
Grand Mean	57	18.312	53.04	60.50
Interaction: Pass	60	13.055	57.60	62.73
Verbal	60	13.055	58.00	63.09
Physical	49	13.055	46.28	51.4.1
Appearance:				
Mechanoid	51	10.830	48.71	52.98
Humanoid	62	10.486	60.11	64.24
Control: Robot	57	18.870	53.39	61.07
Human	56	21.069	52.02	60.60
Direction: Front	58	20.510	54.12	62.47
Side	55	18.433	51.44	59.04
Preferences:				
Mechanoid	60	17.393	46.80	54.22
Humanoid	56	17.946	61.57	69.22
Short	61	18.349	53.56	61.3.8
Tall	55	16.967	54.81	62.0.5
Initial Uncertainty	71	67.770	57.04	84.27

From Koay et al. [31], Syrdal et al. [3], Walters et al. [30] and Walters [34].
Note: These values have been compensated to make the distance measures directly comparable.

Table 2 RH Approach Distances vs. Interaction Context

approach distance estimate can be calculated for a robot encountering any combination of proxemic factors in the first column. For example, consider the case where a Humanoid robot approaches a human to hand over an object. Note the factors which apply, then calculate the default approach distance for the particular situation and context. In this case, the distance would be: (Base distance =) 57cm + (Humanoid-RH Approach =) 3cm - (Giving Object RH Approach=) 7cm = 53cm. If other any other factors are known (e.g. if the preferred height was short, then adjust by -1cm), then they can also be incorporated into the calculation. As other factors which affect HR proxemics become known or quantified, they can be incorporated into the model and used to refine or extend the applicability of the proxemic estimates produced. For example, the robot's voice style has already been shown to affect HR proxemics [30] and it is likely that gender and gestures by both human and robot may well affect HR proxemic behaviour, as is the case for human proxemics [8].

If a particular factor is not known, then it is wise to err on the side of caution and assume that the furthest distance would apply. An approach that was was too close might be interpreted as invading personal space, while an approach that was slightly too far away would be perceived as keeping a respectful distance. For example, if a person's preference for height is not known, it is safest for the robot to assume that their preference is for small robots as this would ensure that any error in approach distance positioning by the robot would result in an approach distance that would be further away than might actually be preferred. It should also be straightforward to incorporate (modified) rules, with appropriate weightings for Hall's social and public spatial zone distances to provide for appropriate proxemic behaviour by the robot over larger distances in open areas and for different physical situations [35]. The framework also lends itself to incorporating other different scales for the rating of robot appearance (e.g. realistic-iconic, realistic-abstract or machine-organic dimensions, cf. [36] & [37]).

This method assumes that the HR proxemic factors are linear

Factor	Situation(s)	Context(s)	Base Distance = 57cm Estimated Adjustment for Factor (± 0.5cm)
Attribute or Factor of Robot			
Mechanoid Robot	RH Approach HR Approach	All	-3 -7
Humanoid Robot	RH Approach HR Approach	All	+3 -1
Verbal Communication	RH Approach	Verbal Interaction	+3
Giving object	RH Approach	Physical Interaction	-7
Taking object	RH Approach	Physical Interaction	-7?
Passing	RH Approach	No Interaction	+4
Direction from:	RH Approach	Front Right/Left	+2 -2
Attribute or Factor of Human			
Preferred Robot Humanoid	RH Approach	All Private	-3
Preferred Robot Mechanoid	RH Approach	All	+3
Preferred Height Tall	RH Approach	All	-1
Preferred Height Short	RH Approach	All	+2
Uncertainty or perceived Inconsistency	HR Approach	Initial Encounter	+13
Verbal Communication	HR Approach	Verbal Interaction	+3
Giving object	HR Approach	Physical Interaction	-7?
Taking object	HR Approach	Physical Interaction	-7?
Passing	HR Approach	No Interaction	+4

? *Indicates an estimated value based on the observation from our earlier study [28][29] that RH and HR approach distances were highly correlated and exhibited a high degree of symmetry between HR and RH approaches.*

Table 3 Factors Affecting HR proxemics

and independent. However, the number of robot types studied here is too few to make any conclusions as to the form (linear or otherwise) of the relationships between the factors examined (e.g. robot appearance) and the precise numerical value of their effects. There are also indications that some of the factors are dependent on each other. For example, from [38] it was found that the preferred robot appearance and actual robot appearance factors have a combined effect on HR approach distances (Table 2). In this case a practical approach would be to apply a correction if both factors are present, possibly by means of a look up table. It should be noted that few real world systems actually exhibit linear behaviour, but often by assuming a linear response, a reasonably precise control output can be obtained without having to implement more sophisticated non-linear control methods.

The values provided in Table 3 are obtained from our controlled HRI trials and the numbers of participants for the relevant experiments are relatively large compared to those typically found in HRI trials of this type. However, it is desirable to perform approach distance experiments with a much larger experimental sample, and with a large number of robots with different appearance and behaviour attributes to properly establish the range, form and parameters of HR proxemics. To perform the required number of experimental runs, it will be necessary to implement fully autonomous robot control and automatic data collection methods for future experiments.

Another issue is the large variance observed for both the Grand Mean and for the marginal means in these samples (Table 2). This suggests that individual differences between participants play a large role in determining proxemic preferences in any given instance of an HRI encounter. This makes the study of systematic variations in proxemic preferences according to measurable individual differences factors, such as personality and demographic data, as well as more HRI specific factors like the NARS [39] or UTAUT [40] scales, a salient avenue of investigation in order to establish a HR proxemic framework with greater predictive power.

3 IMPLEMENTATION OF A HUMAN-ROBOT PROXEMIC SYSTEM

In order to test, verify and extend the application range of the empirical HR proxemic framework, the next stage would be to conduct live HRI experiments, with a HR proxemic control system based on the empirical framework implemented on a range of robot platforms. Mitsunaga et al. [41] implemented an adaptation mechanism based on policy gradient reinforcement learning for robot proxemic and gaze behaviours using initial default parameters for HR proxemics based on Hall's social spatial zones. Their system illustrates the viability of using an adaptive control system to refine initial default values for proxemics for particular HRIs based on empirically obtained default values. However, we propose that a prototype implementation using a fuzzy logic based control system might be particularly well suited for verification and further research purposes. The various HR proxemic factors could be incorporated by means of fuzzy rule sets. The weightings of the factors could then be dynamically "tuned" by means of a number of well known learning algorithms (cf. [42] [43]), possibly using actual real time user feedback (cf. [44]). This would provide a learning mechanism so the robot could effectively adapt its proxemic behaviour to individual users preferences and requirements. The advantage of a fuzzy logic based control system is that as the robot becomes acclimatised to the proxemic preferences of more users, contexts and situations, it is possible to interrogate the fuzzy system proxemic factor weightings, and thus work back to estimate and explore the relationships between HR proxemics and the factors. Fine adjustments of human-robot interpersonal distances according to a number of observed factors (as proposed by Walters et al. [28]) related to the internal qualities of the interacting humans, intrinsic robot attributes, the external physical situation and the task context, is a worthwhile contribution towards the goal of a robot companion that can be individualized, personalized and will adapt itself to the user as suggested by Dautenhahn [45].

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