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Characteristics of Personal Space during Human-Robot Interactions: A Systematic Review

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Abstract

The purpose of this study is to conduct a systematic review of the personal space characteristics of human-robot interactions (HRIs) based on the PRISMA guidelines. A systematic literature search was conducted in October 2023 using the following databases: ProQuest, ScienceDirect, PubMed, IEEE, MDPI, and EBSCO. The following keywords were used: "personal space", "social interaction", "human" AND "robot", and "human-robot". The inclusion criteria were as follows: 1) studies involving HRIs, 2) studies using social robots, and 3) studies exploring personal space during HRI. The research was conducted on articles published between 2013 and 2023. The search yielded 329 articles, and 58 articles underwent a thorough full-text review. Of these, 34 studies did not meet the eligibility criteria, leaving 24 studies eligible for data extraction and analysis. Three themes were identified regarding the characteristics of personal space when humans interact with robots: 1) specific human-robot comfort distances, 2) factors that influence human reactions during HRI, 3) different reactions of human during HRI. The human-robot distance did not differ significantly from the human-human distance in this systematic review. As social beings, humans unconsciously reserve personal space. However, human-robot distance will continue to be studied due to the current low robot penetration and function. The social nature of robots in human society is underdeveloped. Nevertheless, people are confused by robots' emotional expressions and react by distancing themselves from them. It has been suggested that humans move, talk, and find the robot or animal-like elements there, and unconsciously maintain a comfortable distance for themselves.

Keywords

Human-Robot Interactions, Human Responses, Personal Space, Social Robots

1. Background

Society 5.0, which is being promoted by the Japanese government, is a human-centered society that balances economic development and the resolution of social issues through a system that highly integrates cyberspace (virtual space) and physical space (real space). Society 5.0 uses AI (artificial intelligence) to analyze big data, including various types of information such as real-time physiological measurement data of each individual, information from medical sites, medical and infection information, and environmental information [1]. One of the goals of Society 5.0 is to enable people to lead comfortable lives by themselves through the use of robots that assist them in their daily lives and talk to them. Japan's declining birth rate and the increasing older adult demographic are anticipated to result in a shortage of nursing and professional caregivers needed to support older adults [2]. In numerous sectors, the anticipated "robot revolution" holds the potential to address the increasing shortage of personnel [3]. Consequently, nurses now need elevated levels of knowledge, intelligence, and familiarity with technologies, including artificial intelligence, to provide high-quality nursing care [4].

Those responsible for designing healthcare facilities should be particularly mindful of the growing reliance of nursing professionals on technological advancements in their daily practice. For example, efficient and precise machines equipped with artificial intelligence support a technology-centered society, leading hospitals and healthcare systems to become increasingly reliant on technology. This reliance affects the quality of healthcare and patient care satisfaction. Therefore, nurses require higher levels of knowledge, intelligence, and recognition of technologies and artificial intelligence to provide quality nursing care [4]. With the development of AI, the field of robotics is evolving at a remarkable pace, and socially assistive robots (SAR), which can understand human language and engage in conversations with older adults who are being introduced in nursing care facilities [3]. In response to growing demands, SAR technology has the potential to play new roles in the health and social care sector. However, the reported value of SAR in older adults' care warrants further investigation. Future research should strive to validate the role suggested by previous studies. By "reported value", we mean information from previous studies and reports describing the actual effectiveness and benefits of social-assistive robots (SARs) in the care of older adults. On the basis of these reported values, it is important to gain a better understanding of the value that SARs can provide in the care of older adults. However, questions remain as to how reliable this reported value is and whether it has been properly assessed. Therefore, further research and verification are required. This will provide a clearer understanding of whether SARs are indeed useful in the care of the elderly and how to use them effectively.

Social robots, especially humanoid robots, hold promise for addressing the psychosocial needs of older adults and individuals with dementia in health and social care. SAR has the potential to contribute to the health and well-being of the elderly and improve their quality of life; SAR may address issues such as loneliness and dementia and help seniors lead more comfortable and fulfilling lives. This is also the value of SARs [5] [6] [7]. Despite their potential, there is limited evidence on the implementation of these robots for older adults. As service robots become more common, interaction design needs to cater to novice users, emphasizing trust for safe and seamless cooperation with robotic systems. The field of social robotics aims to design robots capable of joint interaction with humans [8]. Park and Whang [9] stated that it is vital for robots to be able to empathize with human partners and express congruent emotions accordingly.

Personal space refers to the area around the body that individuals maintain during social interactions with others. When others violate this space, discomfort occurs and the individual acts to reestablish an appropriate social distance. Candini *et al.* [10] showed that the skin conductance response (SCR) increases when others approach an individual's personal space. This suggests that SCR serves as a warning signal for personal space invasion and that there is a functional link between behavioral interpersonal space regulation and related physiological processes. Focusing on the role of gaze in robot-human interactions, Koller *et al.* [11] showed that humans exhibit social gaze behavior regardless of robot gaze behavior. In addition, the robot's gaze behavior had no direct effect on human response or comfort, with different results depending on the degree of gaze aversion. Thus, it is necessary to consider whether similar personal space perception can and should be considered in HRIs.

Interpersonal distance varies depending on the content of the conversation, and eye gaze plays an important role in human-human interaction and HRI as well [12]. There are also functional challenges with robots that are closer distance to the actual human body, such as the possibility of hurting a person through large movements and not always maintaining an appropriate interpersonal distance [13].

One difference between humans and robots lies in the response intensity provoked by intrusion into personal space. Specifically, intrusion into personal space by robots elicits more intense reactions than intrusion by humans [14]. By clarifying the characteristics of personal space when humans interact with robots and the elements that constitute them, we will clarify the environment and the state of the target person when using SARs.

The purpose of this study is to conduct a systematic review of the personal space characteristics of HRIs using social robots.

2. Methods

2.1. Design

This study used a systematic review design and followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (PRISMA) [15].

2.2. Search Methods

A systematic literature search was conducted in October 2023 using the following databases: ProQuest, ScienceDirect, PubMed, IEEE, MDPI, and EBSCO. The following keywords were used: "Personal Space" [Mesh], "Social Interaction" [Mesh], "human" AND "robot," and "human-robot."

2.3. Inclusion and Exclusion Criteria

Studies were included in the review based on the following eligibility criteria: 1) studies involving HRIs, 2) studies using social robots, and 3) studies exploring personal space during HRI. The search was limited to articles published in English between 2013 and 2023. Articles found in grey literature, conference proceedings, books, book chapters, reviews, and dissertations were not included.

2.4. Study Screening

The researchers used Covidence to import and organize all study citations identified through the search strategy. Covidence [16] is a web-based collaborative platform designed to facilitate the creation of systematic and other literature reviews. In the initial phase, five reviewers (RY, AB, YK, LB, and TT) individually assessed the eligibility of each study based on the titles and abstracts. Subsequently, the reviewers independently examined and evaluated the complete text of the eligible articles and make provisional decisions on their inclusion. CSY reviewed and edited the current manuscript for consistency. The six authors then convened to reach a consensus on the final selection of studies to be included.

2.5. Data Extraction

Three reviewers (RY, AB, LB) independently collected the data utilizing a data extraction form. Any discrepancies were resolved by mutual agreement. The extracted data included the title, authors, country, objectives, design, description of HRI, outcome measure, and key findings.

2.6. Data Analysis

Data analysis was conducted through a narrative analysis of the HRI, outcomes, and key findings.

3. Results

3.1. Search Outcome

The search produced 329 articles, and after eliminating 27 duplicates, 302 articles underwent title and abstract screening. Following the exclusion of 222 irrelevant studies, 58 articles underwent a thorough full-text review. Among these, 34 studies did not meet the eligibility criteria, resulting in 24 studies eligible for data extraction and analysis. The PRISMA flow diagram in Figure 1 illustrates this process.

3.2. Characteristics of the Reviewed Studies

The identified literature came from several countries and was all published articles with an experimental study design. They conducted studies based on HRI that explored the themes of personal space or proxemics, approach trajectory, and accompanying factors that may affect human physical and mental/emotional comfort during HRI. Some studies measured their outcomes through subjective reporting, such as questionnaires and evaluations using Likert scales. In contrast, others applied qualitative measurements from motion-captured videos and applications of their proposed algorithms or models.

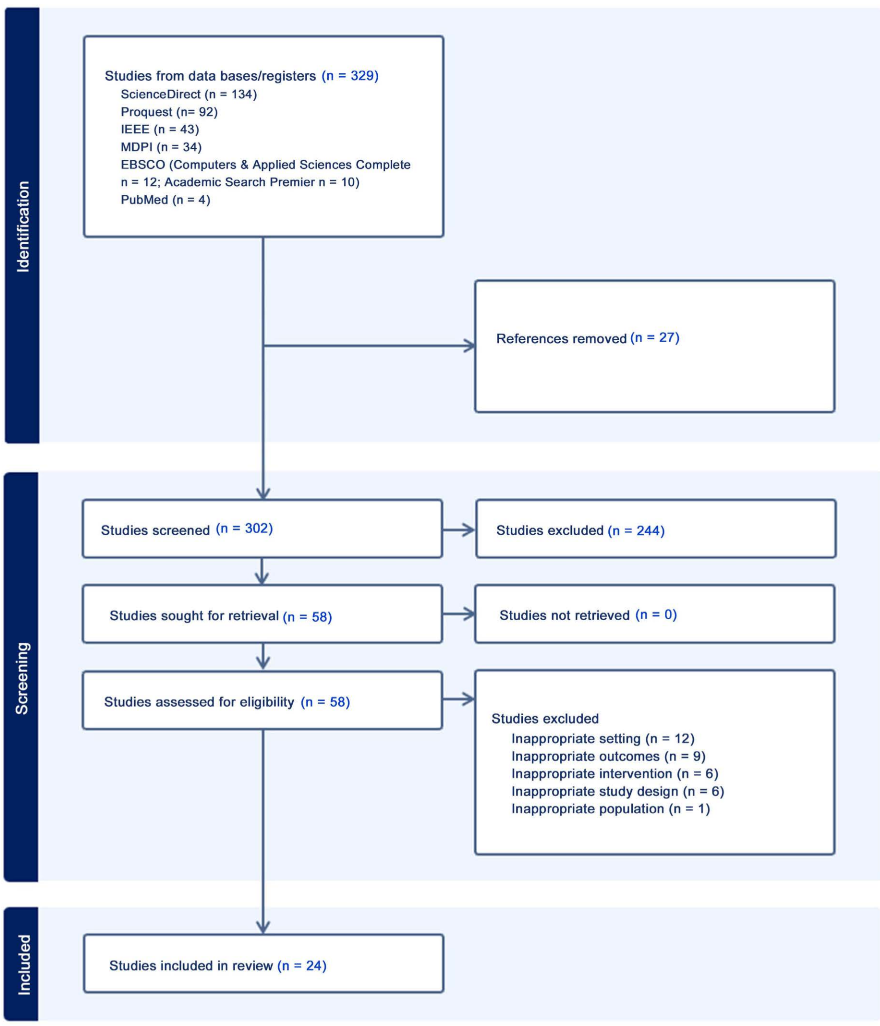

Figure 1. PRISMA flow diagram.

The following studies have dealt with determining the distance that humans deem acceptable for robots to interact with them. Iachini *et al.* [17], Pazhoohi *et al.* [18], Manawadu *et al.* [19], Lauckner *et al.* [20], and Kamide *et al.* [21], sought to determine the distance human participants deemed comfortable when a robot approached them for communicating. They either used virtual robots, real robots, or a combination of both along with other stimuli and analyzed subjective feedback from the human participants to collect their thoughts on the interactions.

On the other studies hand, others applied the concept of personal space and comfort distance to their algorithms and systems to determine the effect on HRIs [22] [23]. Tanaka *et al.* [23] sought to determine whether a human operator's intimate zone could be mirrored to the android robot they are operating, while Daza *et al.* [22] applied proxemic zone concepts, trajectory, and human feedback data to design an algorithm for a self-navigating social robot.

Other studies [24] [25] [26] [27] have focused on the robot's ability to comfortably approach or avoid humans. The researchers tested situations where robots would pass humans in different approach trajectories, and the human subjects would subjectively evaluate their experience through a manner of ranking scores and evaluation instruments. Ahn *et al.* [28], on the other hand, used machine learning algorithms to train robots on how to comfortably approach humans. They then applied it to human motion simulators along with the actual robot and human subjects. Sekiguchi *et al.* [29] applied their machine learning method to allow the robot to follow and track the humans they were following while maintaining a non-obstructive distance and test it through simulated and actual situations.

The rest of the studies focused on human perception and factors that affect comfort levels during HRI. These studies involved HRI through games [30] [31], following commands, or a listening activity [32] [33], and human subjects were asked to rate and evaluate robots based on certain indices or scoring metrics. Joosse *et al.* [34] observed attitudinal and behavioral responses using a proposed social instrument in which a human or robot invaded a participant's personal space. **Table 1** shows the details of the included studies.

4. Discussion

This study identified three themes regarding the personal space characteristics of HRIs: 1) Specific human-robot comfort distances of each author (5 papers), 2) Factors that influence human reactions during HRI (3 papers), and 3) Different reactions of humans during HRI (6 papers).

4.1. Specific Human-Robot Comfort Distances

Tanaka *et al.* [23] found that when other people approach a highly human-like android robot, which is operated in synchronization with human motion, the operator sometimes feels as if he/she is being approached. This suggested that the personal space of the participant was formed around the android by the synchronized operation.

Yoshida *et al.* [33] reported that the closest distance between the human and robot was set at 30 cm. In the study by Banik *et al.* [37], the average distance was 69.31 cm when the human was stationary and the robot was moving. On the other hand, the distance increased to 79.75 cm when the robot's eyes were glowing red to indicate an angry state.

Participants approached the robot at five different distances (threat distance, near distance, standard distance, slightly far distance, and far distance), while seated in a chair, and the distances that caused discomfort from two robots of different types were 58.00 cm and 36.25 cm [24]. Based on the results of this experiment, the standard distances were 91.50 cm and 58.00 cm, respectively, and the distance between the person and the robot corresponds to the individual distance proposed by Hall [41].

Kamide *et al.* [21] compared psychological evaluations from interactions between a virtual robot and a real humanoid robot and determined the amount of personal space the subjects desired from the robot. This virtual robot is a computer-generated or simulated robot that exists within a virtual environment, such as the Cave Automatic Virtual Environment (CAVE). In the CAVE, motion tracking systems are commonly used to measure the space between a human and a virtual robot. These systems track the movements and positions of both human and virtual robot in real-time, allowing researchers to analyze the positional data and determine the spatial distance between them. Additionally, the 3D images displayed in the CAVE contribute to spatial perception, allowing participants to visually gauge the distance between themselves and the virtual robot. They subjectively assessed their impressions on the basis of a psychological scale as the robots approached them from varying distances. They included three approaches from a distance such that the robot will pass by the participant, from the front-center direction and from the midpoint. In assessing the personal space, they measured the distance that indicated when the subjects started feeling uncomfortable as the robots approached them. The subjects generally thought that the real robot had greater utility, possibility of communication but had less controllability than the virtual robot. In terms of personal space, there was no difference in desired distance between the subjects and either the real or the real robot. The robot was 7.802 cm and the average distance the subjects wanted between themselves. Manawadu *et al.* [19] reported similar findings when they applied a computational model for a side-by-side walking HRI based on proxemics. Starting from a preset comfort zone of 80 cm determined from previous studies, the robot was able to maintain a comfort zone radius between 79 cm and 81 cm after analysis with robot-captured real-time data and human subject feedback. Lauckner *et al.* [20] explored the minimum threshold of comfort distance for frontal and lateral approaching robots and found that the mean frontal distance (77 cm +/− 27.5 cm) was higher than lateral distance (40 cm +/− 12.5 cm).

Table 1. Characteristics of the included studies.

Title	Author/s	Country	Objectives	Study design	Interaction	Outcome Measure	Key findings/ Characteristics of Interaction
Body Space in Social Interactions: A Comparison of Reaching and Comfort Distance in Immersive Virtual Reality	Iachini *et al.* [17]	France	Do peripersonal space for acting on objects and interpersonal space for interacting with conspecifics share common mechanisms and reflect the social valence of stimuli?	Experimental	Participants judged reachability and comfort distances toward human and non-human virtual stimuli, both while standing still (passive) and walking toward stimuli (active).	This study assessed participants' stopping behavior in Reachability and Comfort tasks under Active and Passive conditions using an Immersive Virtual Reality (IVR) system. The system tracked participants' positions and recorded the distance between the head-mounted display marker and virtual stimuli in real-time.	Peripersonal reaching and interpersonal comfort spaces share a common motor nature and are sensitive, to different degrees, to social modulation. Therefore, social processing seems embodied and grounded in the body acting in space.
Change of Personal Space Induced by Operation of Android Robot Synchronized with Operator	Tanaka *et al.* [23]	Japan	To verify whether an android operator's personal space could also be formed around the android by the operation in synchronization with him/her.	Experimental	An experimenter approached the android to the intimate distance after participant became familiar with the synchronized operation.	1) Subjective reporting: The subjective reporting in the synchronous condition was measured by the questionnaires 2) Skin conductance response (SCR): The SCR was sampled at 10 Hz via an A/D converter synchronized with event signals of the approach by the experimenter.	The personal space of the participant was formed around the android by the synchronized operation.
Direct comparison of psychological evaluation between virtual and real humanoids: Personal space and subjective impressions	Kamide *et al.* [21]	Japan	To compare psychological evaluations of a robot constructed using a virtual reality (VR) system (VR robot) with a real robot.	Experimental	Three approaches: from a distance such that the robot will pass by the participant (Approach 1); from the midpoint between Approach 1 and 3 (Approach 2); and from the front-center direction (Approach 3).	The study used the PERNOD scale to evaluate human impressions of robots, comparing perceptions between virtual reality (VR) and real robots. Video analysis (30 frames/s) measured desired personal space, including the duration until the participant pushed a button, the distance the robot walked (d), and the remaining distance between the participant and the robot (D).	Results showed no significant difference in personal space between the two robots, forming a circular pattern with an average distance of 780.20 mm. Subjective impressions favored the VR robot's controllability but rated lower for utility and communication compared to the real robot. Scores for vulnerability, clumsiness, and objective hardness did not differ significantly between the two.
Exploring a Comfort Zone in Side-by-Side Communication for Human-Robot Interaction	Manawadu *et al.* [19]	Colombo, Sri Lanka	To develop computational model for side-by-side walking within human-robot interaction based on proxemics.	Experimental	The experiment was divided into two sessions. In the first session (session 01), a comfort zone of 80 cm was chosen based on previous studies in the Asian region. In the second session (session 02), the experiment was repeated with varying distances between the human and the robot.	1) Data Captured by the System: The system recorded data such as the X coordinate of the human relative to the camera frame and the distance between the human and the robot. 2) Feedback of Participants: A questionnaire collected participant feedback on personal information, personal space preferences, and familiarity with social robots.	The robot efficiently maintained a comfort zone radius between 790 mm and 810mm, aligning with the preset value of 800 mm preferred by participants.
Give me space: Sex, attractiveness, and mind perception as potential contributors to different comfort distances for humans and robots	Pazhoohi *et al.* [18]	UK, Canada	To shed light on a discrepancy in the research on comfort distance preference in relation to robot-human interactions.	Experimental (Across two studies the paper systematically explored)	Participants rated female (Study 1) and male (Study 2) humanoid robots and human avatars at distances ranging from 50 to 250 cm, for comfort and attractiveness.	[Study 1] Participants used a 7-point scale to rate comfort and attractiveness while observing human and robot stimuli at various distances. The self-paced rating task comprised 42 trials, covering 2 agents across 21 distances. [Study 2] Alongside attractiveness ratings, participants assessed human and robot stimuli on agency and experience using a 0 to 100 slide scale for each trait.	Comfort ratings are positively associated with distance for both female (Study 1) and male agents (Study 2), and participants reported higher comfort for humans than humanoid robots.
'Hey robot, please step back!' - exploration of a spatial threshold of comfort for human-mechanoid spatial interaction in a hallway scenario	Lauckner *et al.* [20]	Edinburgh, UK	Exploration of a minimum threshold of comfort for frontal as well as lateral approach distances for a mechanoid in a hallway.	Experimental	During all frontal distance conditions subjects were asked to drive the robot towards themselves and stop it as soon as they started feeling uncomfortable without correcting the robots position after the initial stop. During the lateral distance conditions they were asked to position themselves along a marked line on the floor as close to the passing robot as it starts getting uncomfortable without correcting their own initially chosen position.	Paired t-tests revealed significant differences in scores for both lateral and frontal distance conditions, with frontal distances consistently higher. Mean lateral distance was 0.40m (SD = 0.125 m), and mean frontal distance was 0.77 m (SD = 0.275 m).	A threshold of comfort for frontal as well as lateral distances exists in human-mechanoid interaction in a hallway scenario. No interaction effects of velocity and personal space occurred.

Continued

An Approach of Social Navigation Based on Proxemics for Crowded Environments of Humans and Robots	Daza *et al.* [22]	Peru	To describe proposed approach and show how proxemics and the classical navigation algorithms are combined to provide an effective navigation, while respecting social human distances. To show the suitability of our approach, we simulate several situations of coexistence of robots and humans, demonstrating an effective social navigation.	Experimental	The proposal in this research is focused on the development of a navigation system for social robots acting in environments populated by both humans and robots. The proposed approach considers that the robot must avoid collisions in a social environment and incorporates restrictions based on proxemics, in particular for robot–human interaction for the greater comfort of people.	This paper employs two metrics: Lratio, comparing the lengths of paths generated by the A* planner and the modified algorithm; and Smooth, assessing the smoothness of robot movement based on mean angles. Lratio is defined in Equation (1) as the ratio between the path lengths of A* (DA*) and the social navigation algorithm. The Smooth metric, calculated using Mean Square Error in Equation (2), evaluates the smoothness of robot movements as it deviates and returns to the A* path, considering the mean of angles (θi) and the number of angles measured.	Carefully designed proxemic behaviours in robots might foster closer human–robot relationships and enable widespread acceptance of robots, contributing to their seamless integration into society. However, when the robot is sharing the same environment only with other robots, it is not necessary to consider social restrictions. Thus, an effective social navigation should adapt to these situations.
Modeling a Pre-Touch Reaction Distance around Socially Touchable Upper Body Parts of a Robot	Cuello Mejía *et al.* [35]	Japan	To identify the minimum comfortable distance in human–human touch interaction around the upper body.	Experimental Statistical analysis	The toucher slowly stretched out a hand toward the evaluator's body part; when the evaluator wanted the approaching hand to stop, he/she generated an audible signal by clicking a button. When the toucher heard the signal, he/she stopped immediately his/her hand, returned to the initial position, and continued the data collection.	They used two OptiTrack systems (Acuity Inc.) as a motion capture system to automatically track the positions of the body parts of both the touchers and the evaluators.	The minimum comfortable distance around the hands is smaller than the minimum comfortable distance around the shoulders and elbows. Gender and angle factors did not show a significant effect. These results exhibited a similar phenomenon with a past study about pre-touch reaction distance around the face. The parts factor, only for the distance around the hands, showed a significant difference in the shoulder and elbow distances. The movement speed showed a weak impact in the minimum comfortable distance, and the acclimation effect also showed a significant difference.
Am I acceptable to you? Effect of a robot's verbal language forms on people's social distance from robots	Kim *et al.* [36]	Korea	To examine the effect of robots' language forms on people's acceptance of robots	Two-by-two between groups experimental design	How people's acceptance of robots varies according to the social distance between the human and the robot implied by the robot's verbal language forms.	On the post-experiment survey, participants rated the robot on 64 different Likert-type items regarding to robots' interpersonal traits: dominance and friendliness. Robots' interpersonal traits were calculated with those items by formulas.	Calling people by their name caused them to perceive the robot as a socially conversational entity. In particular, when a robot calls people's names in a familiar speech style, people perceive the robot as friendlier, actively interact with it, and allow it to be within a closer distance.
Determination of Active Personal Space Based on Emotion when Interacting with a Service Robot	Banik *et al.* [37]	Bangladesh	To ascertain how this distance will be optimized, whether there will be any advantages gained by achieving this, whether the optimization will help to improve the condition of robots, how humans will react, what effect emotional states will have on APS (Active Personal Space), etc.	Experimental	The determination of active personal space (APS) for a service robot based on emotional status. APS means the active distance (relative distance during interaction and action) between the robot and the human.	In the experimental procedure, one human subject was asked to move towards the robot as if he or she needed to talk with it. The human was asked to stand along the scaled line, look at the robot face and move closer to it until the proximity was such that the subject felt uncomfortable or unsafe. In this case, the human was moving and the robot was standing.	The relationship between the human and the robot is likely to change as time passes, much like inter-human relationships. Thus, it is important to observe the relationship between human and robot in an environment where long-term interaction is possible. The results of incorporating the robot into such a constantly participating human environment may be entirely different to interactions that occur in a short time period. With an increasing number of interactions of a person with a robot, the Active Personal Space may be reduced as familiarity is increased with the interactive robot.

Continued

Do Not Let the Robot Get too Close: Investigating the Shape and Size of Shared Interaction Space for Two People in a Conversation	Ruijten *et al.*[38]	Netherlands	To experimentally study the shape and size of the shared interaction space of two people in a conversation.	Experimental	During the conversation, a robot will be approaching them from different angles until it is stopped at a comfortable distance by both people.	Torta and colleagues developed a paradigm to directly measure the optimal distance of approach. This paradigm for measuring optimal stopping distances for two people in a conversation.	In most cases, they do so, as seen by larger stopping distances when the robot approaches from behind the other person.
Human-Robot Interaction in Industrial Settings: Perception of Multiple Participants at a Crossroad Intersection Scenario with Different Courtesy Cues	Alves *et al.* [39]	Portugal	To investigate how different kinesic courtesy cues (stop, decelerate, retreat, and retreat and move to the left) would be understood in the view of two participants with different perspectives of the robot (one with a frontward view and the other with a backward view) at an industrial crossroad under the same test conditions, *i.e.*, within one simultaneous scenario.	Experimental	Participants performed five test conditions within a total time of 20 minutes. They initiated the test upon hearing a "Beep" and seeing a green light. To ensure encountering the robot at a designated point on the navigation map, participants were instructed to walk at a pace set by evaluators, approximately 1 m/s.	To measure the participants' perceived trust in the AMR (Autonomous Mobile Robots) behavior, they applied an adapted version of the HTA (Human Trust in Automation) questionnaire. Comparatively to the original questionnaire, we replaced the word "system" by "robot". The HTA is a validated questionnaire composed of 12 statements, assessed by a 7-point Likert scale (between 1 = "Totally disagree" and 7 = "Totally agree").	Statistically significant association in the sense that a higher percentage of participants showed hesitant behavior when they saw the robot from behind (61.2%) than when they approached from the front (41.2%).
Online Learning to Approach a Person With No Regret	Ahn *et al.* [28]	South Korea	To propose a novel method for a robot to learn in comfortably approaching a human based on their personal preferences; to introduce the concept of "personal comfort field" and to propose an online method for learning the personal comfort field of a user based on GP-UCB	Experimental design based on Gaussian regression and simulations	Human motion simulator; robot and humans (users)	Users' evaluation scale on approaching behavior between robots with and without learning	The proposed method allows the robot learn each user's personal comfort field through repeated encounter and approach trajectory adjustments. There was significant improvement in user satisfaction about the quality the robot's approach trajectory.
Personal Space Violation by a Robot: An Application of Expectation Violation Theory in Human-Robot Interaction	Asavanant *et al.* [24]	Canada	To extend Expectation Violation Theory (EVT) to Human-Robot Interaction (HRI) and to examine the effects of personal space violation using EVT as an analytical framework.	Experimental	Participants were approached by the robot at five different distances (threat, near, norm, slightly far, and far distances) in randomized order. The participants were asked to evaluate their impression of the robot after each approach.	Communication outcomes were operationalized as evaluations of robots and were measured by Robotic Social Attribute Scale (RoSAS).	Depending on how the robots' reward value was perceived, the effects of personal space violation would also differ. Personal space violation can occur both by being too close or too far, and that the extent of the violation (how far or how close the distance is) have influence on the outcomes of the violation. However, whether the direction and the amount of deviation affect the communication outcomes positively or negatively would depend greatly on the robot's reward value.
The effect of robot speed on comfortable passing distances.	Neggers *et al.* [26]	Netherlands	To investigate the relationship between passing distances of robots and the experiences comfort of humans.	[Experiment 1] Repeated measures Analysis of Variance (rANOVA) [Experiment 2] Full-factorial Analysis of Variance (ANOVA)	[Experiment 1] Participants were instructed by a computer to walk in a specific direction (left or right of a temporary wall) and on a designated line (red or blue). A robot, starting from the opposite side, passed the participant at a constant speed. [Experiment 2] Participant walked across a room, and the robot began either from the same side or the opposite side based on the scenario (passing or overtaking).	[Experiment 1] Participants were asked to rate their agreement with two statements on a 7-point Likert scale: "I felt comfortable passing the robot" and "The robot passed me at a comfortable distance". [Experiment 2] Participants were asked to answer one question on a 7-point Likert Scale: "How comfortable were you with the passing of the robot?" Additionally, we used location trackers of Phase Space Motion Capture, to track the location of the participant with respect to the location of the robot.	Clear effect of passing distance on perceived comfort, measured both subjectively and through behavior. The effect can be modeled using an inverted Gaussian, which only depends on two parameters. The moving speed of the robot affects these parameters, showing lower comfort levels overall for higher moving speeds. People are furthermore less comfortable with the robot overtaking them, than with the robot passing them.

Continued

Determining Shape and Size of Personal Space of a Human when Passed by a Robot	Neggers *et al.* [25]	Netherlands	To determine the shape and size of personal space of a person when the robot is passing by.	Experimentally investigate	How robots can avoid a person in a comfortable way	The robot's Passing distances were measured from the center of the human to the center of the robot.	Comfort increased with distance. Especially in the case of the humanoid robot, passing at the back of a person feels less comfortable than passing at the front, which makes the shape of personal space not circular. The humanoid robot coming from the back is perceived as less comfortable compared to coming from the front.
Pedestrian Dominance Modeling for Socially-Aware Robot Navigation	Randhavane *et al.* [27]	America	To present a Pedestrian Dominance Model to identify the dominance levels of pedestrians to facilitate socially aware navigation for robots; To present an application of PDM (Pedestrian Dominance Model) for generating dominance- based-collision- avoidance behaviors in the navigation of autonomous vehicles among pedestrians.	Experimental design using multiple linear regression	Trajectory information and dominance level perception of pedestrians; robot navigation algorithm.	Pedestrian dominance model (PDM).	Formulation for socially aware robot navigation is based on prior work in psychology literature, which states that complementarity in dominance increases the rapport and comfort between interacting partners; PDM can be applied in navigation robots to predict pedestrian behavior in interactions between autonomous vehicles or self navigation robots and pedestrians.
Uncertainty-aware Nonlinear Model Predictive Control for Human-following Companion Robot	Sekiguchi *et al.* [29]	Japan	To propose a control method for companion robots that enables natural front-following despite an uneven human walking trajectory	Experimental design	Human walking trajectory, robot; simulations and actual.	Ability to follow (Navigation distance), predict walking direction (Tracking error of position) and maintain a non-obstructive distance (Uncomfortable time); application to a robot system.	Human walking prediction results were not significant; in simulations and in real-robot experiments, the uncertainty-aware control method can avoid obstructing the human's walking path and avoiding delay
BEHAVE-II: The Revised Set of Measures to Assess Users' Attitudinal and Behavioral Responses to a Social Robot.	Joosse *et al.* [34]	The Netherlands	To evaluate human responses to robot behaviors in order to assess whether they are experienced as socially normative.	Controlled between-groups laboratory experiment	A human-robot interaction experiment was conducted in which a robot or a human invaded the personal space of a participant.	BEHAVE-II, for assessing user responses toward a robot's behavior using both attitudinal and behavioral responses.	Participants' reactions were stronger when their personal space was invaded by a robot compared with a person. This points to the fact that humans are actually highly sensible whether robots' adhere to social norms, which underlines the importance of the BEHAVE-II instrument.
Breathing Expression for Intimate Communication Corresponding to the Physical Distance and Contact between Human and Robot	Yoshida *et al.* [33]	Japan	To verify the factors related to "intimacy" for a robot's expressions based on verification using the two factors of physical distance and contact.	Experimental	Participants listened to the voice of the robot for about ten seconds with breathing expressions for each condition. After each session, the experimenter kept the robot and the participant answered the evaluation items by using MOS (means opinion score).	The participants evaluated the robot in each condition using a five-point scale rating of the relevance (5: very relevant, 4: somewhat relevant, 3: even, 2: somewhat irrelevant, 1: irrelevant). Evaluation items for of the semantic differential (SD) method: The participants evaluated the impression for "intimacy" using a five-point scale rating for each adjective pair.	The close-distance communication provides some uncomfortable situations through the too-vivid expressions that make it seem real. From the factor analyses of SD, the impression for intimacy is affected by the "Friendly" factor and the "Calmness" factor.
Do you feel safe with your robot? Factors influencing perceived safety in human-robot interaction based on subjective and objective measures	Akalin *et al.* [30]	Sweden	To investigate the relationship between these factors and perceived safety in human-robot interaction using subjective and objective measures.	Two-by-five mixed-subjects design experiment	The experimental scenario consisted of playing a quiz game with a robot. The between-subjects conditions were the faulty robot experienced at the beginning or at the end of the interaction.	Questionnaires, physiological sensing, and facial affect metrics of the participants for evaluating perceived safety.	Extraverts have a more positive mood in the interaction. People with a high neurotic personality felt less safe and less in control. If there is prior knowledge about the participants, the robot could be less proactive when interacting with neurotic people to give them more control.

Continued

How social distance shapes human–robot interaction.	Kim *et al.* [31]	Korea	To investigate how social distance can serve as a lens through which they can understand human–robot relationships and develop guidelines for robot design.	A two-by-two (power distance: supervisor vs. subordinate; proxemic distance: close vs. distant) between- subjects- design experiment.	Playing a card matching game with the robot.	The paper assessed task performance using two indices: the total number of mistakes and total game duration. For measuring participant experience with the robot, a questionnaire gauged satisfaction, likeability, comfort, and pleasure. Likeability, comfort, and pleasure scales included items assessing participants' preferences and satisfaction levels during the game. Responses were recorded on seven-point rating scales. A post-experiment questionnaire measured participants' rapport with the robot.	The study found that user experience improved when the supervisor robot was close and the subordinate robot was distant. Task and proxemic distance manipulations yielded unexpected results, with better user experience when competitive robots were close and cooperative robots were distant, contrary to prior literature predictions. Additionally, cooperation negatively impacted participant task performance.
Human Response to Humanoid Robot That Responds to Social Touch	Okuda *et al.* [32]	Japan	To investigate the effect of robot's reactive behavior to human contact on the impression of the robot and mood of the person interacting with it.	Experimental	The experimenter and participant stood adjacent to each other, and the robot stood in front of the participant. The participants interacted with the robot according to the instructions of the experimenter.	The study utilized nine seven-point semantic differential scales, such as Dislike (1)–Like (7) and Foolish (1)–Clever (7), to gauge participant responses. Feelings were recorded after each session using scales like I felt anxious (1)–I felt relieved (7) and I felt restless (1)–I felt relaxed (7). Participants also completed a questionnaire, assessing their emotions conveyed to the robot and the robot's understanding of emotions, using seven-point scales. Another aspect inquired about the participant's preference for the robot to gain, using a seven-point scale from Do not agree at all (1)-Completely agree (7).	Male participants tended to stroke the robot's head, while female participants often stroked or held the robot's hand to convey "happy" emotions. For "sad" emotions, both genders touched the robot's hand frequently, engaging in slow movements like stroking. Expressing anger involved forceful actions, such as grabbing the arm or hand strongly. Male participants typically touched the robot once, while some females touched multiple times or various parts of the robot's body to convey specific emotions. Only female participants grabbed and swung the robot's arms and hands.
Two Age Groups Comparison on Impression Evaluation of Distance and Communication with Two Different Appearance Mobile Robots	Uchikawa *et al.* [40]	Japan	To evaluate the impressions when communicating with a robot and observe the influence of differences in appearance and distance in causing human behavior among two age groups	Experimental design	Robot (humanoid and non-humanoid- looking) -human communication	Likeability, impression of distance, warmth and discomfort and change in impression of the robots through the experiment through Likert scale	The older subjects preferred the robots closer in proximity, while the younger group was uncomfortable to have the robot at close range; The robot with the higher eye level upon approach made some subjects uncomfortable; The older subjects had a better impression of the humanoid robot, while the younger subjects preferred the wheeled mobile robot with a computer screen face display.

Iachini *et al.* [17] sought to determine through virtual stimuli whether reachability distance (for potential action such as touching objects, reaching out, or manipulating items, refers to the possible actions or behaviors in interactions with objects or individuals.) and comfort distance (for social interaction such as handshakes, conversations, and eye contact, pertains to people engaging with others, communicating, and exchanging interactions.) are different between human and non-human stimuli. Among the non-human stimuli, they observed whether the distances between an anthropomorphic robot and a cylindrical object were different for male and female subjects. They found that the subjects would maintain a larger distance when the stimuli were approaching them than if they were approaching the stimuli and that they maintained the largest distance from the cylinder, the least perceived to be human-like, in all aspects. A larger comfort distance was maintained when the subjects were approached by the stimuli. Between the stimuli, the shortest distance was maintained between the virtual female human and the robot.

Pazhoohi *et al.* [18] explored more on comfort distance and explored whether participant sex, robot sex, attractiveness, and mind perception change the distance between HRIs. They found that individuals generally feel less comfortable interacting with robots than humans, and attractiveness, and mind perception to robot interaction play a role to this. Their findings also did not show any differences in comfort ratings between male and female robots, and the comfort distance between the subjects and robots were around 280 cm and 300 cm for male and female robots, respectively.

It was considered that people perceive robots as social individuals when interacting with them and maintain the same distance from them as they do when interacting with humans.

4.2. Factors That Influence Human Reactions during HRI

When a person speaks to the robot, the distance between the person and the robot changes, and people perceive the robot as a social interlocutor when it is called by name [36]. In addition, when the robot calls a person's name in a friendly manner, people perceive the robot as friendly, and the distance between the person and the robot increases. It has also been shown that as the adoption rate of HRIs increases, habituation to the interactive robot may occur, and active personal space (APS) may decrease [37].

Thus, the personal space between humans and robots is expected to change depending on the relationship. Nonverbal communication, such as facial expressions and distance, is important for communication [42]. However, it is also important to improve the natural language processing ability of robots, such as speech, vocabulary, and the ability to listen to human words in conversations with interactive robots [43].

4.3. Different Reactions of Humans during HRI

HRIs have shown that comfort distance from robots is influenced by factors such as a robot's likability, gaze behavior, and attractiveness [18]. Across two studies ($N = 443$), this study systematically explored whether the type of agent (human vs humanoid robot), agent's sex, and distance influence comfort ratings. Comfort ratings were positively associated with distance for female (Study 1, $N = 170$) and male agents (Study 2, $N = 273$), and participants reported higher comfort for humans than humanoid robots.

A previous study has shown that participants in this study react more strongly when their personal space is invaded by a robot than by a human [34]. In addition, studies have shown that the faster the robot moves, the lower the overall comfort level with the robot, and that people are more afraid of being overtaken by the robot than of overtaking the robot [26].

These findings suggest that people may be thinking about whether robots are social beings and taking a critical view. However, the current study is limited because it did not identify the human psychological and cultural factors that influence HRI. Future research should also investigate how human psychological and cultural factors influence HRI. Future research should be conducted on the characteristics of personal space in human-computer interaction, including participants from different cultural backgrounds, age groups, and genders.

5. Conclusion

This study aims to determine the characteristics of personal space when humans interact with robots. The human-to-robot distance was not significantly different from the human-to-human distance in this systematic review. As social beings, humans unconsciously reserve personal space. However, in the current era of low robot penetration and function, human-to-robot distance will continue to be studied. The social nature of robots in human society is underdeveloped. However, people are confused by robots' emotional expressions and react by distancing themselves from them. It was suggested that humans move, talk, and find the robot or animal-like elements there, and unconsciously maintain a comfortable distance for themselves.

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Conflicts of Interest

The authors declare no competing interests.

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