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Proxemics for Human-Agent Interaction in Augmented Reality

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ABSTRACT

Augmented Reality (AR) embeds virtual content in physical spaces, including virtual agents that are known to exert a social presence on users. Existing design guidelines for AR rarely consider the social implications of an agent's personal space (PS) and that it can impact user behavior and arousal. We report an experiment (N=54) where participants interacted with agents in an AR art gallery scenario. When participants approached six virtual agents (i.e., two males, two females, a humanoid robot, and a pillar) to ask for directions, we found that participants respected the agents' PS and modulated interpersonal distances according to the human-like agents' perceived gender. When participants were instructed to walk through the agents, we observed heightened skin-conductance levels that indicate physiological arousal. These results are discussed in terms of proxemic theory that result in design recommendations for implementing pervasive AR experiences with virtual agents.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**.

KEYWORDS

Proxemics, Augmented Reality, Personal Space, Virtual Agents, Human-Agent Interaction, Perception

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Figure 1: Participant approaching a virtual human agent (VHA) to greet and ask for directions to an art exhibit. The experiment showed that participants respected the personal space of the virtual agents and pervasive AR design should thus consider proxemics.

1 INTRODUCTION

Augmented Reality (AR) technology enables digital content, from simple 3D objects to virtual human-like agents (VHA), to be embedded into physical space [7, 47]. By virtue of their similarity to humans, VHAs afford natural and intuitive interactions with users, thus serving as an intuitive and unobtrusive system interface. Using human-like virtual agents that mimic humans, i.e. that speak and use gestures, can render human-computer interaction fundamentally social [1, 14, 49, 65]. In other words, VHAs in a physical environment create a social context where users could interact or collaborate with them in the same space [38, 55]. VHAs exert a social presence, i.e., a feeling of being together in a room with another person [25, 51]. For example, participants who have to select one of two physical chairs to sit on often avoid choosing the chair that is digitally occupied by a VHA even though both chairs are viable options in the physical space [47]. Additionally, it is known that higher visual fidelity of the VHAs could increase the perceived level of presence as well as trust [19, 43]. However, if visual realism is not aligned with the behavioral, i.e., VHAs do not adhere to social norms, it could lead to a decrease in social presence. For example, collision of VHAs with objects in physical space, such as an agent walking through a door to appear in a closed room could break the

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user's perceived social presence that could only be mitigated by applying a fade-in/fade-out effect [36].

Reducing the sense of presence means negatively impacting the continuous, or pervasive social experience in AR [21, 47]; furthermore, the issue of rendering plausible physical-virtual scenarios becomes more salient in the case of AR telecommunication where the system displays 3D scans of remote users, e.g. Holoportation [52], as it could soon be used for real-time communication. For instance, Reinhardt et al. investigated which location is desired for displaying virtual representation of remote users and concluded that users preferred to visualize the virtual human representations that they are communicating with frontally [58]. As such, it remains a challenge as to how VHAs should be positioned without occlusions or conflicts with the physical surrounding because maintaining a degree of presence is key for an engaging social interaction experience.

Proxemic research, the science of how people utilize space, suggests that people occupy an invisible area beyond their body. Humans often maintain a personal space (PS), a circular region with a radius of 1 m, that serves as an invisible buffer from one another [23, 28, 71]; moreover, intrusion into this space causes discomfort and arousal [13, 27].

Interestingly, this extends to immersive virtual environments (VR) too. In VR, human users demonstrate a PS of 1 m [4, 9, 30] when approaching VHAs and violations of PS can produce strong physiological arousal as indicated by an immediate increase in skin conductance levels [13, 60]. This importance of PS for social interaction raises the following questions: Do VHAs occupy a PS even if they do not occupy physical space in the AR environment? What happens when PS is violated in AR? Our research questions (RQ) are as follows:

RQ1: Do people respect VHA's PS ([30]) in AR as if they would keep a distance with strangers in real life (interpersonal distance (IPD) >1 m)?

Hypothesis 1: Naturalistic human-human proxemics patterns are observed in AR when participants approach the VHAs, specifically that users would keep a distance of >1 m from the VHAs.

Hypothesis 1.1: VHAs occupy a PS of around 1m evidently when participants approach to interact with them.

Hypothesis 1.2: The distance the participants keep from the VHAs is modulated by the gender of the virtual agent (male agents induce a larger distance compared to the female agents).

Hypothesis 2: Non-human like agents, i.e., pillar and robot invite a larger IPD compared to that of the human-like agents.

RQ2: Does violation of VHA's PS increase participant's level of physiological arousal as compared to that of the non-human agents?

Hypothesis 3: Violating the PS of a VHA will lead to an elevated physiological arousal [60].

In this paper, we present the results of an experiment (N=54) in which participants interacted with VHAs and an control object, see Figure 2, in an AR art museum setting. We found that PS is respected when participants approached the VHAs to ask for directions. Also, the preferred IPD of the participants could be modulated by social features, such as the perceived gender of the virtual agents (Block 1 & 2). This was shown as the individuals' preferred IPD at which they passed the VHAs varied (Block 1). In our study we also compared the degree of physiological arousal indicated by skin conductance response at two levels: when the participants walked past the VHAs, versus when they were required to walk through the VHAs. Violation of space by walking through the VHAs increased the participants' skin conductance level, reflecting physiological arousal. Drawing from proxemics literature, we discuss our findings in terms of what it means to display VHAs at an appropriate distance so that it respects the social-spatial norms and how our results may inform designers in the future for creating a comfortable human-agent interaction in an enclosed AR space.

Figure 2: Six virtual agents used, including (from left to right) two female and two male agents, one humanoid robot, and one pillar. The name abbreviations are as follows: F1, F2, M1, M2, Robot, Pillar. The choice of virtual objects was motivated by prior research that compared VHAs to a cylinder and a robot, see [32].

2 RELATED WORK

2.1 Human-Human Proxemics

The term "proxemics" was first coined by Edward T. Hall to describe how people utilize space to communicate with other people [24]. He quantified four zones of interaction based on individuals' interpersonal distances (see Figure 3 and 4), which include 1) intimate distance (touching - 0.46 m), 2) personal distance (0.46 m - 1.22 m), 3) social distance (1.22 m - 2.40 m), and 4) public distance (>2.40 m). In particular, "intimate" space is the space one would keep with his or her romantic partners, "personal" space is reserved only for his or her friends and family, "social" space is the space in which one interacts with acquaintances or strangers, and lastly, "public" space is the space in which one can address others during, for instance, public speaking on stage. In a more recent study, Hecht et al. empirically showed that PS boundaries can be refined [30]. They observed that it spans a circular-shaped boundary with a radius of about 1 m around the person when encountering strangers.

Social stimuli, such as culture, gender or emotional expressions could alter the size of the PS and preferred IPD [28, 59]. For example, Cartaud and colleagues showed that interpersonal social distance can be sensitive to emotional valence, i.e. angry facial expressions lead to a choice of a larger IPD keeping [13]. Therefore, PS is flexible and dynamically regulated.

Importantly, violation of PS by a stranger often causes arousal or discomfort [26, 28]. This perceived discomfort is measured experimentally by the stop-distance technique [29]; furthermore, it can be quantified and modeled as a function (namely the "intrusion-discomfort" function) of IPD between two interacting strangers [26, 71]. Welsch et al. presented 15 distances and obtained subjective ratings of discomfort from participants [71]. The results of the rating showed that participants felt most comfortable at IPD between 1 m and 2 m. When the approach becomes very close, the gradient of discomfort is steeper; however, it becomes shallower when the approach, or the preferred IPD is further, or not close enough. This gradient was uniform when scaled to the individual size of PS. Therefore, this suggests that IPD in a given environment is regulated by the level of perceived comfort or discomfort [13, 27, 71]. IPD preference, i.e. the size of PS, presents a local minimum in that function.

2.2 Proxemics in Virtual Environments

Proxemics research has been replicated in virtual environments. Using virtual human-like characters, Bailenson and colleagues tested the inverse relationship between mutual gaze and interpersonal space in immersive VR [4]. In an experimental paradigm, participants walked around in virtual rooms and were required to read the names or remember the virtual human agents' appearances upon encountering them. They found that all participants maintained more space around the agents as compared to non-human-like objects. Additional experiments were conducted to show how agent's gaze patterns could modulate an individual's IPD [5]. These studies suggest that people 1) give more personal space to the virtual humans who engaged them in mutual gaze, 2) maintained a greater distance from the virtual humans when they approached the participants face-to-face, and 3) moved farthest away from the virtual human agents when they violated their personal space in VR.

In virtual environments, violation of PS could create a sense of discomfort in the users. This perceived discomfort can be seen in the participant's physiological arousal. Llobera and colleagues measured the degree of individuals' physiological arousal when approached by four virtual characters including female agents and one cylinder of human size [41]. They found that the number of skin conductance responses, as well as the change in skin conductance level increased in the participants (all male) as the female virtual agents approached towards them. Bönsch et al. showed that a single or a group of three virtual agents with angry and happy facial expressions led to larger and smaller IPD, respectively [9]. Together, these studies show that personal space and comfortable social distances are similarly modulated by social factors in virtual environments like in the physical world.

2.3 Virtual Human Agents

Virtual humans can influence our behavior. Volonte et al. showed that a crowd of virtual humans exhibiting positive social characteristics i.e., pleasant facial expressions, eye contact, etc., appeared to be more inviting as indicated by the duration of the interaction [68]. Miller et al. showed that in the presence of a VHA, participants could solve fewer hard anagram tasks as compared to no VHA; moreover, participants avoided sitting on the chair occupied by a VHA in AR [47]. Garau et al. studied whether aligning visual and behavioral realism can increase human avatar effectiveness [19]. They showed that a naturalistic gaze model increases the perceived quality of communication for high-realism avatars. Wendt et al. evaluated the effect of adding directivity to the source of a virtual human agent's speech sound in an immersive VR setting [73]. Both implicate the degree of the virtual character's behavioral realism can influence an individual's perception.

Implementing real-life proxemic behavior in a conversational virtual agent can also influence how a person interacts and perceives the agent. For example, to study how socially anxious and confident men would react when approached by a woman in VR, Pan et al. pre-programmed an intruding proxemic behavior in a female virtual agent, i.e., the agent initially maintained appropriate conversational distance but later moved closer to the participants. This served the purpose of increasing the level of intimacy in social interaction, which induced stress in the male participants [53].

These studies using virtual agents in VR suggest that the appearance of the virtual character could influence the way users engage in social interaction. Yet in AR, the realism of virtual agents may still be perceived differently as they stand in contrast to a physical environment; furthermore, whether and how they occupy PS need to be investigated for designing favorable social interaction in AR.

3 STUDY

We conducted a within-subjects study to explore how individuals interact with each of the six virtual agents (see Figure 2) in a stop-distance task embedded in an art gallery context. The primary variable of interest is user's proxemic patterns divided into two indicators: distance when the user approaches and greets standing in front of the virtual agent, and the spatial distance when the user walks past the agent to view the art exhibit. The former measures the preferred IPD while the latter measures the minimum distance the user kept with the virtual agents. We are also interested in examining the degree of perceived comfort when walking through the virtual agent. Thus, individuals' arousal as indicated by their physiological responses, i.e. electrodermal activity, are measured. In addition, the Big Five personality questionnaire [62] was included in the post-experiment survey to serve as potential explanatory variables for individuals' distance variations besides their gender and age. Lastly, we are interested in the users' subjective perception of the virtual agents and the perceived quality of interaction with the agents. For this, the participants rated the likeability of each agent; furthermore, questions on believability, co-presence and interaction experience [8] were included in the post-experiment questionnaire.

3.1 Participants

We invited 54 participants (34 female, 20 male) from local universities through mailing lists and flyers. The participants were between the ages of 20 and 43 (*M*=26, *SD*=3.96), with body heights between 153 cm and 193 cm (*M*=168.69, *SD*=8.53). 41 participants had very limited prior experience and knowledge with AR/MR systems (e.g., Microsoft HoloLens), while the remaining had some (N = 6) to plenty (N = 9) prior experience. Before the study, the visual acuity of the participants were measured from a distance of 3 m using the

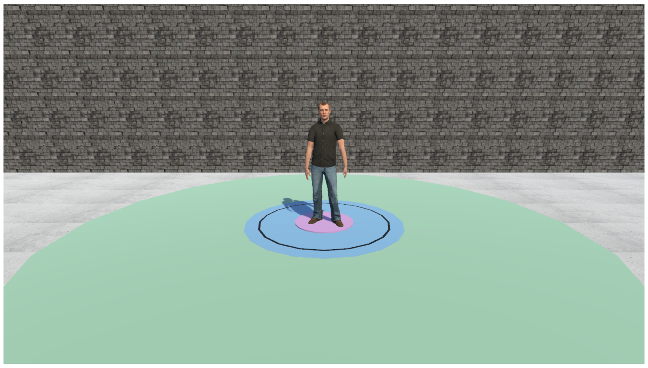

Figure 3: Interpersonal distances according to Hall [24]: intimate distance (purple), personal distance (blue), and social distance (green). Black circle indicates 1 m boundary according to Hecht et al. [30].

Freiburg Vision Test 'FrACT' (version 3.10.5) [3] (M_{logMAR} = -0.21; SD_{logMAR}= 0.09; decimal acuity = 1.6) to ensure they have normal or corrected-to-normal eyesight. None were excluded based on low vision (all decimal acuity > 0.1). All participants received 10 € as compensation for their participation. The local ethics committee approved the study.

3.2 Procedure

Before the study began, the researcher welcomed the participant and provided written information about the study as well as instructions to complete the stop-distance task. The study information sheet includes brief information about the study, what is AR/MR technology, and anonymized data collection, while the task instruction sheet includes instructions on how to complete the task. After the participant read through the documents, the researcher repeated all the information again verbally and gave the participant the consent form to sign. Pre-experiment survey questions, such as the participant's gender, age, height, knowledge of AR/MR, ID number for the experiment, were provided digitally on Qualtrics[1]. The participant accessed the survey through a pre-made QR code and answered accordingly on their own mobile phone.

Later, the researcher prepared the part of the distal site of middle and index fingers by applying an electrolyte solution (Potassium chloride 3 mol / l (3 N)) and waited for 10 minutes for optimal hydration of the skin [17] before attaching the electrodes. Then the participant's visual acuity was measured and recorded; furthermore, the researcher also familiarized the participant with the use of the HoloLens 2 and demonstrated once on how to complete one trial of the task[2].

The experiment began after the researcher entered the participant ID in the application on the HoloLens 2 and handed the headset to the participant. The experiment was split into two blocks: Approach (Block 1) and Walk-Through (Block 2). In the Approach block (Block 1), the participants were required to approach, or walk towards the agent from an initial distance of 2.5 m until they feel a comfortable distance was reached for verbal interaction with the virtual agent. Behind the virtual agent stands two art exhibits, one on the left and one on the right (Fig. 6). Note that the initial distance was set to 2.5 m to mimic real-life interaction with strangers from a public distance outlined by Hall [24]. In the Walk-Through block (Block 2), the procedure was the same as the Approach block except that after greeting and listening to the agent's instruction, the participant had to walk-through the body of the agent. Two physical chairs were placed on both sides of the agent to ensure that the participant would in fact walk through the agent.

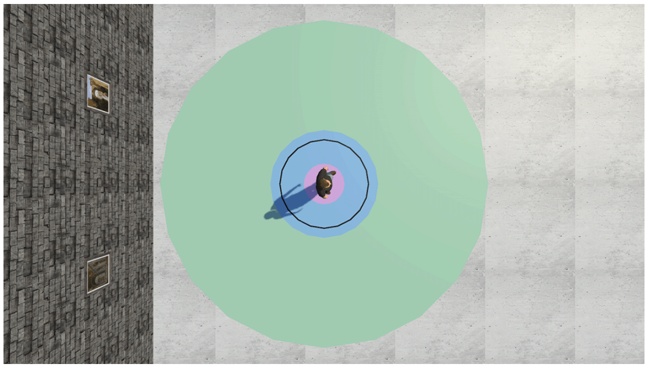

Figure 4: A schematic of the study setup (top view). Please recognize that the wall and floor are only for visualization purposes and are not part of the AR study environment.

When standing in front of the virtual agent, the participant greeted him/her/it by saying "Hello!". This triggered the voice response of the agent instructing the participant to walk past him/her/it in order to examine and verbally rate the art exhibit on a scale of 1 to 5 (5 being the best), i.e. "Hello there, please go to the artwork on the left [right], please rate the artwork." After the participant rated the artwork, there was a short notification sound, which prompted the participant to walk further and turn their body around 180 degrees, standing again from a distance of 2.5m in front of a newly generated set of virtual agent, presented frontally facing the participant, with two artwork pieces behind it. This marked the end of one trial and the beginning of another. See Fig. 5 for illustration of one trial. In total, there were 12 trials with 24 approaches (2 approaches x 6 virtual agents x 2 blocks) as the participants interacted with each of the six virtual agents twice (generated in random order) for both the Approach and Walk-Through blocks.

Finally, after the experiment ended the participants also completed the post-experiment questions that were also part of the same digital survey template as aforementioned.

3.3 AR Environment

Participants were introduced to a total of six virtual agents, including four human-like agents (two males; two females), one humanoid robot, and one pillar (Fig. 2). We selected these virtual agents from the Microsoft Rocketbox library because they are popular and well-used in AR/VR and HCI research [20, 46, 72]. The Rocketbox library consists of 115 fully rigged characters and avatars, out of these avatars there are 42 "Adult" avatars (21 female, 21 male) while the rest are in the categories "Children" and "Professionals". We selected

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[1] https://www.qualtrics.com/

[2] We complied with all COVID-19 regulations and health measures to ensure a safe environment for experimenter and participants.

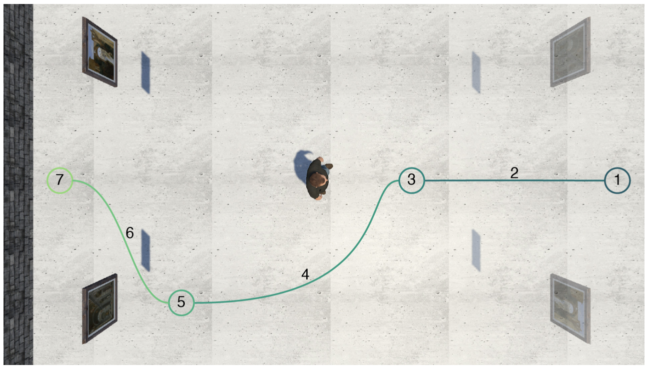

Figure 5: In one trial, the participant starts from a comfortable distance (1) and approaches (2) the virtual agent to greet (3) them and get directions. Then, the participant moves (4) towards one artwork to rate (5) it. Finally, they reposition (6) and turn around (7) to complete the trial. Simultaneously a new agent and artworks are placed in the AR environment.

the avatars from the "Adult" category because we believe these characters match our AR art gallery context the best. Then out of the adult-looking characters, we selected four that we think would resemble our anticipated participants' sample. Having sampled the sex of participants, we could then investigate the interaction between sex of avatar and sex of participant. Nonetheless, due to the low range of age in our participant sample we could not distinguish further how participant age and avatar age might interact.

In a given trial, two virtual art exhibits (Figure 6) were displayed behind the virtual agent, one on the left and one on the right. The artwork pieces were arbitrarily selected from the Metropolitan Museum of Art [50]. Three image targets (one for the virtual agent, two for the 2 artworks) from the Vuforia Engine Library [56] with the patterns: tarmac, stones, chips were printed out on an A4-sized paper and anchored to the floor equally-spaced from each other. Note that all the virtual agents gave speech responses. At the end of all the trials, the application informed the participant by saying, "Thank you, this is the end of the experiment. Please give the HoloLens back to the experimenter."

3.4 Apparatus and Implementation

The apparatus for this study comprised the BITalino biomedical toolkit for measuring the electrodermal activity (EDA), a Microsoft HoloLens 2 to render the AR environment, and a laptop for data recording. To ensure the validity of the EDA recording, we adhered to the recent guidelines for the CHI community [2]. The BITalino biomedical toolkit [22] with the Wireless PLUX Biosignals monitoring platform were used to acquire the EDA signals via Bluetooth connection (biosignalsPlux, PLUX, Portugal). The *OpenSignals (r)evolution* software was used for data acquisition (sampling rate was set at 1000 Hz) and visualization. For EDA measurement, two Ag/AgCl electrodes were attached to the distal phalanx of the middle and index fingers of the participant's non-dominant hand. Data were transmitted via the Lab Streaming Layer framework[3] to laptop PC (Lenovo ThinkPad X1) across a wireless local area network (WLAN) using the User Datagram Protocol (UDP).

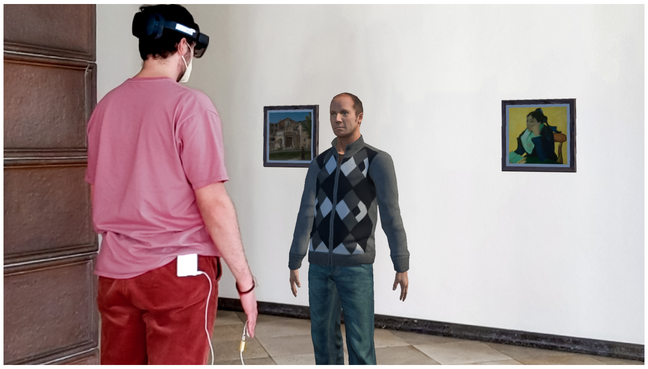

Figure 6: Participant (left) asking the agent (middle) for directions to the next art exhibit (in the background). Participants respected the personal space of agents.

The virtual agents and artworks were displayed through a Microsoft HoloLens 2. Our application and the AR environment were implemented using the Unity game engine 2020.3 [67] integrated with the Mixed Reality Toolkit 2.7 (MRTK) [48] and Vuforia 9.8.8.

The two female and two male human-like agents were selected from the Microsoft Rocketbox Avatar library that provides high definition, fully rigged human-like avatars. We used Adobe Mixamo [64] to set the human- and robot-like agents as idle with a neutral facial expression. Female agents are 172 cm in size, while male, robot, and pillar are 180 cm tall. All virtual agents are depicted in Figure 2.

Natural voice interaction with the virtual agents and artworks was realized using the MRTK build-in speech command capabilities. For each virtual agent, appropriate voice responses (male/female WaveNet; Basic) were prerecorded using Google Cloud Text-To-Speech API. We used Vuforia Engine to seamlessly place the agents and artworks based on printed fiducial markers in the physical space. During the study all assessed data including the position and orientation of the HMD and interaction with the environment was streamed via UDP to the laptop to fuse this data streams with the EDA data. The results of the analyses can be found online on the DaRUS Open Data Platform, at [31]. The same link includes behavioral, qualitative and physiological data. The AR environment including the study apparatus can be found on GitHub[4].

3.5 Expected Behavior

We expect to see that all virtual objects would occupy a PS and that this PS is respected by the participants via keeping an IPD of 1 m when they approach the virtual objects. Second, virtual agents with human social characteristics, i.e. face and body (versus a pillar or a humanoid robot) would invite a smaller IPD from the participants when approaching, as well as walking past the agents. Third, in the block where the participants walk through the virtual agents,

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[3] https://github.com/labstreaminglayer/

[4] https://github.com/pknierim/Proxemics-for-Human-Agent-Interaction-in-Augmented-Reality

participants would exhibit physiological arousal, as indicated by higher skin conductance level. Lastly, we expect gender effects i.e., participants would keep a larger distance when approaching and walking past the male virtual agents.

3.6 Skin Conductance Analysis

Skin conductance responses were processed after the experiment using the open-source Neurokit Python library [42]. We applied a low pass Butterworth filter (cutoff = 3 Hz, order = 4) to the EDA data alongside a convolutional smoothing filter. The processed EDA signal was then decomposed into its phasic and tonic components using median subtraction following the AcqKnowledge procedure [10]. The tonic component of the EDA signal is a low-frequency oscillation that serves as an indicator of general arousal with a slow and inertial response. The phasic component on the other side, consists of higher frequency oscillations in the EDA signal that typically relate to discrete events.

As there is no fixed onset of the stimulus, we extracted the maximum phasic response amplitude for each agent from the phasic EDA signal within a response window of 3 s before and after they walked through or passed the agent (minimum distance in a given trial). Following the standardized Neurokit pipeline [42], we extracted all peaks in the smoothed phasic component with a minimum amplitude of .001 μV [13].

3.7 Likeability and Perceived Gender

All stimuli, but the pillar, were well liked by the participants, see Figure 7. F1 was judged to be female by 96.08% of the participants, to be male by 1.96% and to be non-binary/third gender by 1.96%. F2 was judged to be female by 94.12% of the participants, male by 1.96%, and non-binary/third gender by 3.92%. M1 was judged to be male by 100% of the participants. M2 was judged to be male by 96.08% of the participants, and female by 3.92%. The robot was judged to be non-binary/third gender by 84.31% of the participants, female by 11.76%, and male by 3.92%. Lastly the pillar was judged by the participants to be non-binary/third gender by 94.11% of the participants, and female by 5.88%.

4 BEHAVIORAL DATA

We report proxemics data from our study in three parts along the encounters. We will first report on IPD preferences when greeting the agent, then on IPD when passing the avatar (see Figure 8 for walking trajectories), followed by EDA analysis when walking through the agent in the second block. Note that the distance was an Euclidean distance computed in Euclidean space between the device's camera position and the center of the virtual agent. We supplement these objective data with qualitative and quantitative subjective feedback on the social presence of the agents.

4.1 Block 1: Approaching the Virtual Human Agent

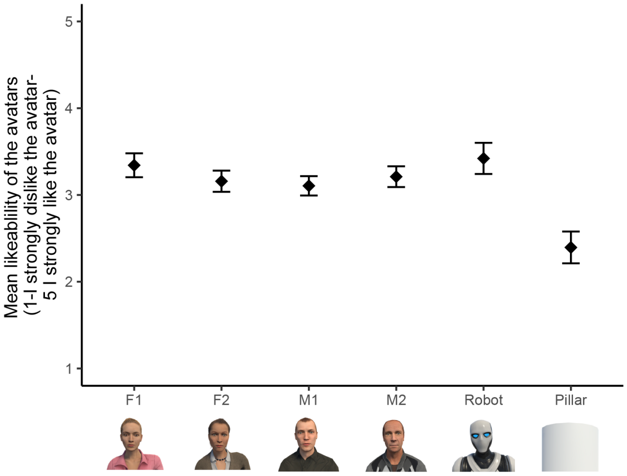

Figure 7: Mean likeability ratings for each of the virtual objects (Likert-Scale 1~5: 1 = "I strongly dislike the agent"; 5 = "I strongly like the agent").

Each subject approached each of the agents four times in both of our blocks resulting in 24 approaches. They walked towards the virtual agent until they felt a comfortable distance to greet him/her/it by saying "Hello". Distances that were above 2.0 m and below 0.40 m (244 trials, 21%) were excluded, as recommended by Welsch et al. [71, 73]. Using the Tukey criterion, for every participant in every condition, trials with distances more than 1.5 times the interquartile range lower than the first or higher than the third quartile were classified as outliers (29 trials, 3%) and excluded from further analyses [66]. Note that such method of trials removal is usual in proxemics literature [13, 73]; moreover, the trials removed included participants (n = 12) who did not complete the full block of 12 trials of the experiment due to technical errors (e.g. speech response non-responsive or application crashes suddenly).

Figure 9 shows the frequency distribution of the mean preferred IPD. Out of the 42 participants, 31 people kept a personal distance (0.46-1.22 m) with the virtual agents, 11 people kept a social distance (1.22 m-2.4 m) with the virtual agents, and none kept a public (>2.4m) or intimate distances (touching-0.46m) with the virtual agents. Figure 10 shows the preferred IPD with respect to all the virtual objects for both the approach and walk-through conditions.

To investigate whether different agents, as well as our control object, take up different proportions of the room, we computed a one way repeated-measures Analysis of Variance (rmANOVA; Type 3[5]) with Agent as a within-subjects factor. Preferred IPD was normally distributed as indicated by a shapiro-wilk test, all W=>0.955 p >=.201. The assumption of sphericity was not met, $M = 0.455$, $p < .01$, which motivates the use the Greenhouse-Geißer corrected degrees of freedom. The analysis revealed a significant difference in preferred IPD between our virtual agents, $F(3.95, 162.14) = 8.24$, $p < .001$, $\eta_p^2 = .17$. Bonferroni-corrected post-hoc t-tests revealed (α /12) that participants preferred larger IPD towards the pillar as compared to both female agents, each $p < .001$, see Figure 10. We found the same difference in comparison to the pillar for male agent 2, $p < .001$. Gender of the agent, likewise changed IPD. We found a significant difference between male agent 2 and female agent 1, $p = .036$.

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[5] We also computed a rmANOVA adding the factor of experimental Block; however, no main or interaction effects with the factor Block emerged, all $p > .05$

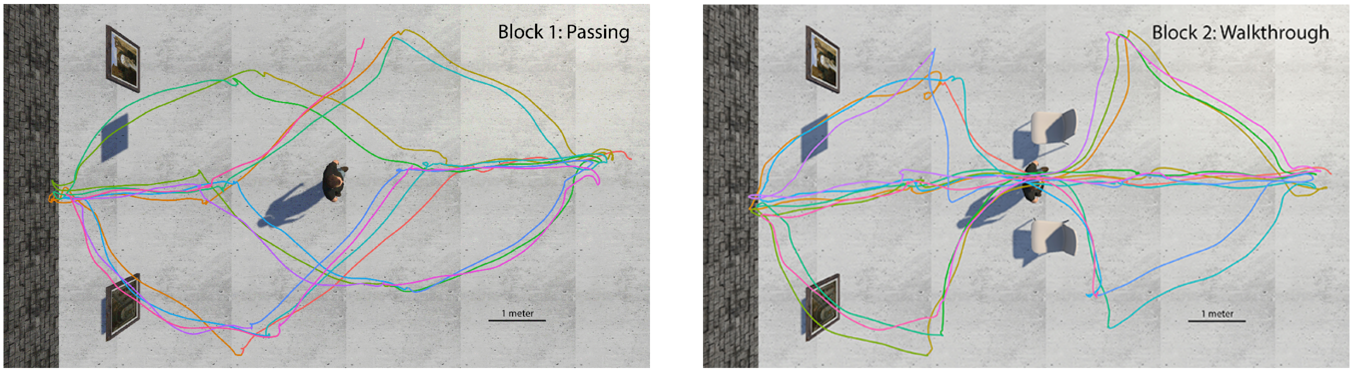

Figure 8: Walking trajectory of one participant for the 12 trials for each both the passing (Block 1: left) and the walk-through (Block 2: right) conditions. In Block 1: Passing participants respected a roughly circular area of 1 m around the VHA

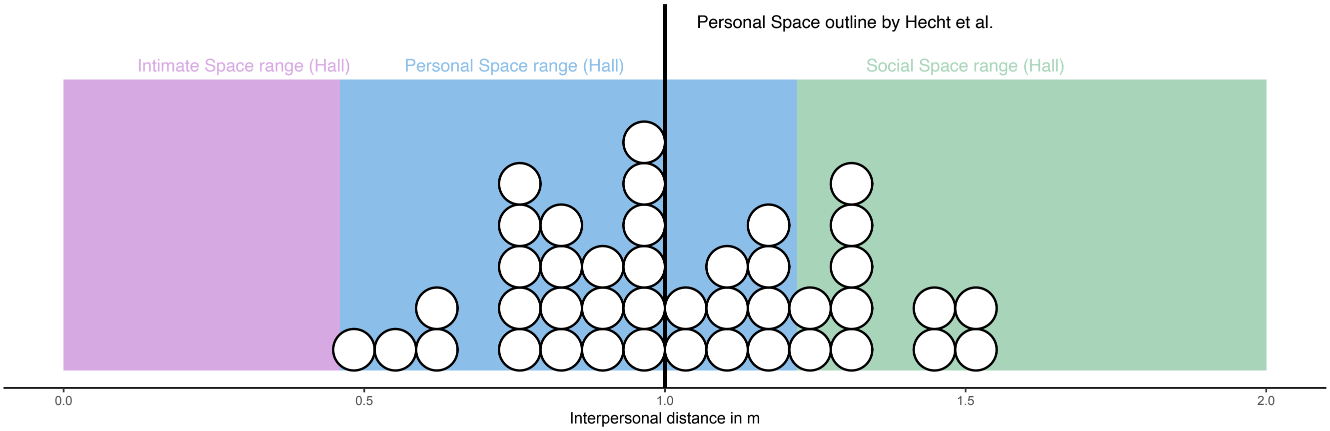

Figure 9: Histogram showing frequency distribution of the participants' mean preferred IPD towards the human-like agents. Out of the 42 participants, 31 individuals kept a personal distance [23] with respect to the virtual objects. Mean IPD was equally distributed across the edges of PS defined by Hecht et al. [30].

Considering that the gender of the virtual agent changed IPD, we ran a separate two-way ANOVA, W<=0.935, p =.137 for preferred IPD on gender of agent (within; female vs. male) and gender effects (between; female vs. male for only our four human-like agents. We found a significant effect for agent gender, $F(1, 40) = 7.73$, $p = .008$, $\eta_p^2 = .16$. Participants preferred larger IPD towards male agents as compared to female agents, see Figure 11. There was no effect of participant gender, $F(1, 40) = 0.17$, $p = .678$, $\eta_p^2 < .01$, and also no interaction effect, $F(1, 40) = 0.00$, $p = .970$, $\eta_p^2 < .01$.

In sum, human-like agents produced smaller IPD when participants approached them to start a conversation as compared to our control object, the pillar (see Figure 2). We also found that IPD was enlarged when approaching male agents as compared to female agents.

4.2 Block 1: Passing the Agent

In the first experimental block, participants passed the agent on either the right or left side to go to the exhibit. Here, we recorded the minimum passing distance for each object. Participants passed each agent 2 times. In total, there were 12 walk-through. For the analysis 8 participants had to be excluded out of the 42 participants (15%), as they did not pass the agent but directly started the next trial. Resembling the prior analysis, sphericity assumption for the model was not met, $M = 0.523$, p =.026, the one-way rmANOVA(within-subjects: virtual object) was significant, $F(3.89, 163.25) = 4.07$, $p = .004$, $\eta_p^2 = .09$. Post-hoc comparisons (Bonferroni-corrected; α /15) showed that there were significant differences when comparing the pillar to two of the VHA's (F1: $p = .039$; M1: $p < 0.01$, see Figure 12), however, there were no significant differences to the other two human-like agents or the robot-like agent.

For comparison purposes, we also computed the mixed model rmANOVA for the gender of the human-like agents (within-subjects) , comparing the gender of participants (between-subjects; normality was met: all W=>0.916 p >=.124). There was a significant interaction for gender of participant and gender of the human-like agent, $F(1, 41) = 5.46$, $p = .024$, $\eta_p^2 = .12$. The main effect of gender of agent, $F(1, 41) = 0.04$, $p = .850$, $\eta_p^2 < .01$ as well as gender of participant,$F(1, 41) = 1.21$, $p = .278$, $\eta_p^2 = .03$, did not reach significance.

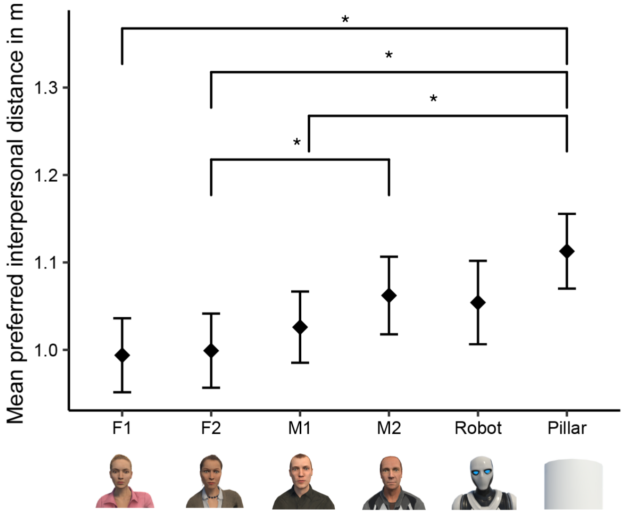

Figure 10: Mean preferred IPD with respect to all the virtual objects for both blocks. Error bars denote +/-1 standard error of the mean. Bonferroni-corrected post-hoc tests (α /12), significant tests marked with "*", show that participants prefer larger IPD towards the pillar as compared to both female agents, each $p < .001$.This was also significant for M2, $p < .001$. M1 and F2 also differed significantly, $p = .036$.

None of the post-hoc tests (Bonferroni-corrected; α /6) was significant, probably due to the slight increase in variance, see Figure 13.

4.3 Block 2: Walking through the Agent

In the second experimental block, we put up physical barriers in the form of two chairs, and asked the participants to walk through the agents. Here, we analyzed maximum amplitude of the phasic component in the EDA as an indicator of physiological arousal. In detail, we extracted the maximum amplitude for each agent in both blocks when passing aside (Block 1) and through the agent (Block 2) in a timewindow of 6s (3s before and after passing aside/through the agents). From the 54 participants, 23 had to be removed due to movement artifacts and excessive noise, leaving 31 for analysis.

Due to violations of normality for the mean of the maximum amplitude, we calculated a two-way rmANOVA (within-subjects factors: Block × Agent) on the aligned rank-transformed data using the ARTool-package [35]. The analysis revealed a significant effect of agent, $F(5, 150) = 2.28$, $p = .049$, no significant effect of Block, $F(1, 30) = 0.836$, $p = .368$, see Figure 14 and Figure 15 for a schematic of one trial. The interaction effect of Agent × Block was not significant, $F(5, 150) = 0.928$, $p = .464$. Bonferroni-corrected Wilcoxon-signed rank post-hoc tests (α /12) did not reach significance, all $V < 389$, $p > .052$.

5 QUALITATIVE RESULTS

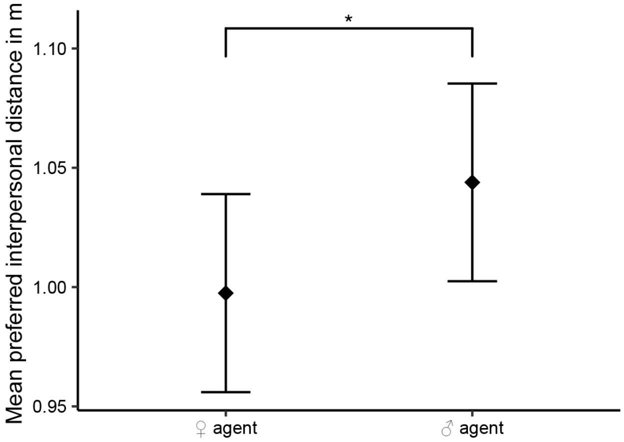

Figure 11: Mean preferred IPD for all human-like agents as a function of gender of agent and gender of participant. Error bars denote +/-1 standard error of the mean. Participants preferred larger IPD towards male agents as compared to female agents.

We report participant's responses on walking-through the virtual agents and analyzed their responses on the believability and likeability of the agents. We did this to understand the participants' preferences and perceptions of the agents. Participants were asked to describe the reasons why they might dislike or like an agent. In finding a virtual agent likable, P41 noted,

> *"I would like Agent 6 (Pillar) the most. Because all I want is less distraction with getting the information. And the 6th had made it..."*

P51 who liked the robot as well as agent M2 described:

> *"I strongly liked the robot because it supplemented the technological theme of the experiment. I also strongly liked Agent 4 (M2) because he felt approachable and friendly."*

Others who have found the humanoid robot likable described how "It is a vivid robot. I feel like I am in a movie" (P17), and that it gives "mild tone and clear instruction" (P20). Some who liked the human agents simply described how they are "human-like" (P44). Some who found the agents not likable also provided their reasons. For example, P51 noted "I only strongly disliked the cylinder because I felt like the interaction was more personal in the case of other agents and this was just an neutral object." P36 described "Agent 2 (*F2*) reminds me of a real person I dislike. Interacting with Agent 6 (*Pillar*) feels like talking to a wall." P18 said that "The robot has the appearance of a robot but not interactive." When asked about their subjective experiences of walking through the virtual objects, several participants reported that it felt unnatural and uncomfortable when they had to walk through the digital content. For example, P10 said,

> *"I felt nervous when approaching the virtual humans, but for the robot it was fine. I felt very awkward when I had to walk through the agents."*

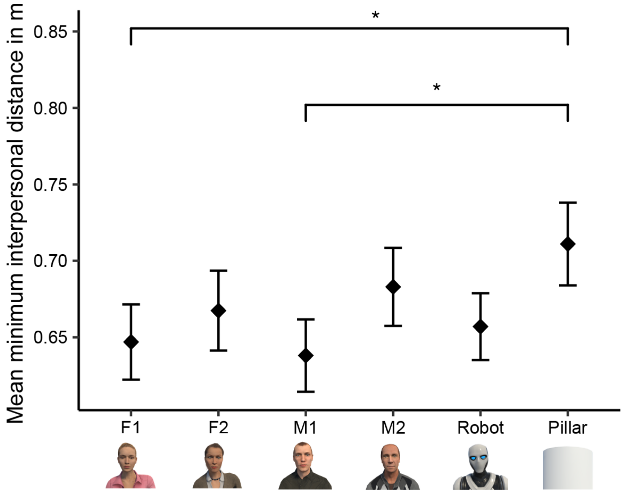

Figure 12: Mean minimum IPD when passing for each the virtual object for both blocks. Error bars denote +/-1 standard error of the mean. Post-hoc comparisons, significant ones indicated with a "*", (Bonferroni-corrected; (α /15)) showed that there were significant differences when comparing the control object to one of female agents and one of the male agents(F1: p= .039; M1: p< 0.01).

P15, P18, P19 also described that they were reluctant to go through the agents. Specifically, P19 noted that HoloLens gave her a realistic and immersive experience. P22 also described:

> *"I did not like having to walk through the agents, especially for the human-like ones; however, for the robot and the cylinder, it was OK."*

Lastly, P13 said that "I was kind of afraid to walk through the agent when wearing the HoloLens. In fact I did not open my eyes." It was observed that this participant kept a large distance from the agents and did not really walk towards the agents.

5.1 Study Limitations

There are a number of limitations that we encountered in the experiment that could be improved in the future. First, the habituation effect from having approached the virtual agents more than 12 times could result in a reduction of phasic response together with the difficulty to control for novelty effect upon seeing the six agents on the individual distances. During the experiment, there were also technical glitches that caused the application to break. Consequently some participants had missing data and were excluded from the data analysis. Another limitation of our work is the field of view (FoV) of the HoloLens display. Although the participants could fully see the virtual agents, the size of the display does not cover the entire visual field including the peripheral view which could influence distance judgment [63]. Additionally, the virtual agents were not intelligently animated (though still showed little movements but essentially static) and showed no emotions. This could cause variability in terms of the subjective perceptions of the agents. Lastly, concerning the choice of the human-like virtual agents: although the Rocketbox library is a popular go-to asset in avatar research, it may still be limited in terms of, e.g. body types, race, ethnicity, gender, and future research should explore a broader spectrum of virtual characters with more diversity (e.g. the Metahumans [18]).

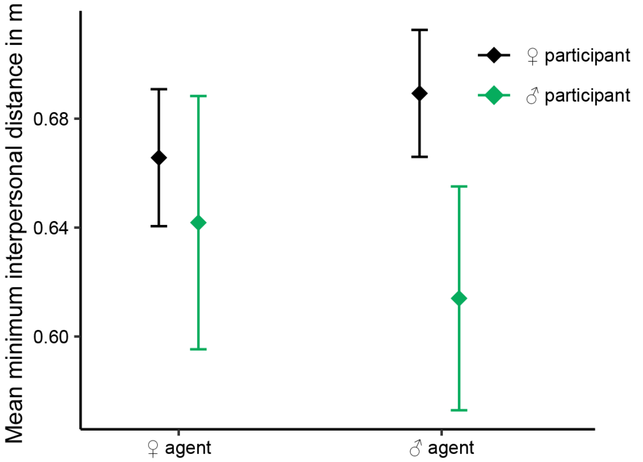

Figure 13: Mean minimum IPD for all human-like agents as a function of gender of agent and gender of participant. Error bars denote +/-1 standard error of the mean. None of the post-hoc t-tests (Bonferroni-corrected; α /6) were significant.

6 DISCUSSION

We evaluated proxemic patterns of participants that interacted with virtual agents rendered within a physical space via a HoloLens. In the study, participants were instructed to approach the virtual agent to greet and ask for directions, walk past (Block1) the agent to the art exhibit and verbally rate the artwork. In Block 2, the participants were required to walk-through the virtual agent after verbally greeting the agent. We did this to understand whether and how virtual agents might occupy a PS, and how this can inform the design of pervasive social interaction experiences in AR. We will first summarize our results, then add our findings to the literature in proxemics in digital spaces. We conclude by summarizing how proxemics play a important role in designing a pervasive AR experience.

6.1 Summary of Results

Our results showed that virtual agents occupy a PS as evident from participant's preferred IPDs. This preferred IPD was modulated according to the social features (i.e. anthropomorphism, perceived gender [30, 33, 72]) of the virtual agents. Participants also kept a larger distance from the male agents in comparison to the female agents when approaching them. This is in line with our first hypothesis and gender-effects in proxemics [23, 28, 30, 72]. Regardless of the gender of the participants, participants kept a closer distance from the human-like agents as compared to the pillar; IPD for the robot was situated in between and did not differ significantly. Such result does not fully align with hypothesis 2 though replicates studies that compared a cylinder and a robot to human-like agents in immersive VR [32]. Lastly, we found that participants

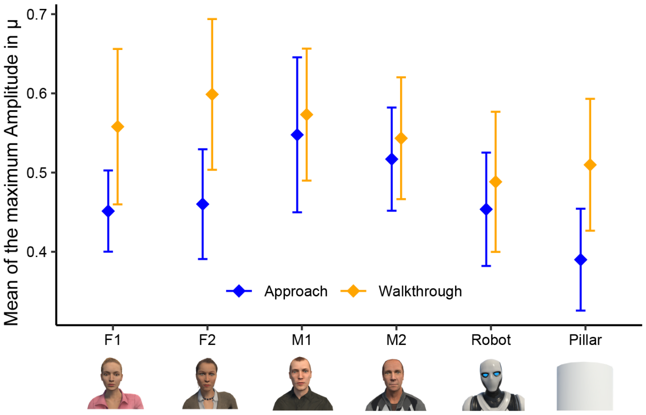

Figure 14: Maximum amplitude for all virtual objects as a function of block. Error bars denote +/-1 standard error of the mean.

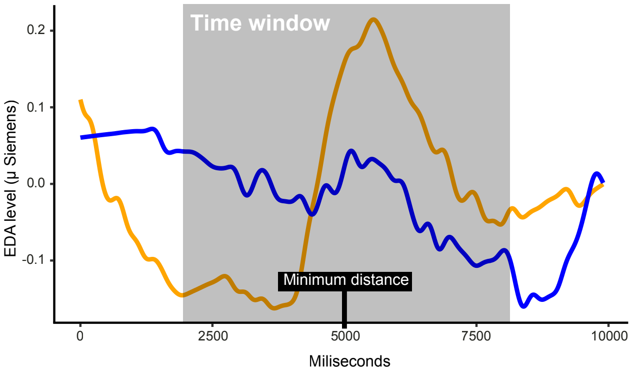

Figure 15: An example of one participant's SCR (P3) when walking through (orange) the agent (F2) as compared to passing the agent on the side (blue).

showed elevated skin conductance responses for some of the agents, which support hypothesis 3 that violating the PS of a VHA leads to physiological arousal.

6.2 Proxemics in Digital Spaces

First, the PS around the virtual agents in AR can be explained by the presence of social features, i.e. face and a body. This is consistent with the literature that imbuing human-like characteristics to virtual agents exert a social presence on users, thus attracts more engagement and interaction from participants [37]. Although the majority of people kept a personal distance with the agents, 11 people kept a social distance with the virtual agents. This variation of preferred IPD could be due to individual's subjective perceptions of the virtual agents [30, 33, 71, 72] as evident from the qualitative responses on likeability of the agents. Though the participants knew that the VHAs are not real, some may have held a stronger perception towards these virtual agents in terms of their visual realism, i.e., size or appearances. For example, P21 noted that "The eyes of the male virtual agents were a little scary. Human-like agents were scarier than the humanoid robot. I was trying to avoid the human-like agents." Hecht et al. [30] report that uncanny-vally effects can indeed increase preferred IPD. Prior work has also suggested that size of the virtual agents matter [70], and that equal-sized human agents are significantly more influential than small-sized agents during human-agent communication as the virtual agents appeared more realistic and persuasive [69].

Research work by Pazhoohi and colleagues further showed that a human agent's height could modulate one's perception of interpersonal dominance, consequently leading to different individual IPDs variations [54]. Together, this means that augmenting virtual agents in a closed space for social AR experience should firstly consider the social features of the agents, as one could expect the agents to possess a PS with a presence that impacts how users decide to interact with the agents and other objects in the environment [36], especially during face-to-face encounters.

Second, PS of the virtual agents are modulated by gender. When participants directly approached the agents, the agent's perceived gender predicted the preferred IPD. However, for the distance when passing the agents, the gender of participant × gender of agent interaction could not be resolved. Such results are in line with [72] that frontal approaches can show stable gender effects. Also, other variables such as the physical size of the room [61] could also influence the preferred frontal distance. Note that the findings on cross gender effect between human-like agents and individuals are mixed in the literature, e.g. Bailenson and colleagues reported larger distances from female agents in VR [5] while Iachini et al. showed that gender and age of the agents modulated people's choice of distances on larger distances from the male agents [33]; nonetheless, one might still expect to have variability in distances due to perceived own and agent's gender. Therefore, to create a comfortable AR social interaction experience, spatial positioning or the PS metric of VHAs based on their gender could be considered.

Additionally, on the line of gender effects, one may argue that it could be confounded by virtual agent's body heights as prior has shown that a short person's PS could be violated more frequently [12]. The present study concerns whether and how virtual agents could occupy PS, and though height could contribute to the differences in individual IPDs, it doesn't explain it alone [11].

Third, walking through the virtual agents descriptively produced higher physiological arousal in the participants (Figure 14 and 15) and that some virtual objects have a heightened propensity to do so. This is in line with prior findings, e.g. Llobera et al. [41] and Cartaud et al. [13] that the PS violations by virtual agents with social characteristics, including emotional stimuli, are capable of influencing people's behavior. Here, however, we report what happens in a scenario where participants have conflicts with the agents by walking through them. This addresses the issue where in an AR context, which combines the physical and the virtual, could negatively impact social interaction because their social affordances of keeping and respecting a PS conflict with task demands. For example, within an enclosed space, such as a small room, the presence of an agent in AR could introduce discomfort in users because the agents might be standing too close to the users. Or, in remote collaborative interaction where crowds of virtual content inhabit the same environment [39, 55] could negatively impact social interaction due to collisions and different physical spatial setups across collaborative AR spaces [36].

Lastly, note that participants maintained a social distance and showed increased arousal towards the virtual pillar (Figure 10 and Figure 14). This is an unanticipated effect which could be explained by the fact that the pillar also gave a speech response when the participant greeted it, resulting in user's anthropomorphizing it which leads to an increase in the perceived social presence. Corroborating this, prior work suggested that the user's attribution of animacy to a virtual agent could be a factor that is responsible for perceiving the agent as a living entity [34, 40].

6.3 Designing Pervasive AR with Proxemics

A pervasive AR interface aims to be aware and responsive to the user's context such that it allows continuous access to information [21]. To create such system, proxemics has valuable potential because it informs designers of the interplay between digital content, the users, and the environment.

First, any digital content that possesses social characteristics, i.e., VHAs, also have spatial quality. The socio-spatial quality of such digital content affords specific actions for the users. Imbuing the virtual agents with a body and a face also means creating a plausible scenario where behaviors should adhere to social norms. For example, imagine placing virtual agents with realistic appearances augmented via AR in a closed space where there might be conflicts with the physical environment, and even with the users themselves. This would cause discomfort in users during interaction because of the implausibility. Thus, accounting for the size of the PS of the virtual content or the preferred IPD variations from the users could lead to a more engaging and interactive experience.

Second, pervasive AR means ever-sharing of digital information in a seamless way. AR/MR technology creates personal and interactive platforms for remote collaboration and information-sharing spatially [55, 57]. Furthermore, sensing technology for 3D capture in synergy with capable AR headsets allows users to interact with remote participants. Developments such as Holoportation [52] or Mesh [15] could soon be adapted for real-time communication. Nevertheless, privacy could become a concern on this continuum. Respect for others' PS becomes important when users attempt to teleport into each other's space. Here proxemics could be leveraged (creating a proxemics-aware AR environment) to encourage positive social interaction, e.g., higher visual fidelity and social presence of virtual contents when distance gets closer but also not producing discomfort.

Third, given that socio-spatial relations are dynamic and can result in arousing events (i.e. agents approaching into user's intimate zone), incorporating physiological computing could allow for proxemics-aware systems to detect and adapt seamlessly user's IPD to physiological arousal. This perspective also envisions hyper scanning scenarios [6] to redirect multiple users for comfortable distance, scaling digital space and consequently creating more pleasant experiences in real-time.

6.4 Conclusion and Future Directions

In the future, other dimensions of proxemics, such as orientation (directional information), movement (change in distance over time), identity (discriminates between categories) and location (e.g. context or situation) could be investigated for human-agent interaction in AR but also social AR [44, 45]. These proxemic metrics can be used to guide or initiate social interaction with the VHAs. This would require studies that examine the mutual approach of VHA and the user, mimicking real-life human-to-human communication, e.g., two people notice, greet and approach each other. Here, social cues such as gaze and body gestures may be integrated to increase user engagement. In addition, future work could also investigate more the role of speech response in human-agent interaction for social AR as prior research suggested that intelligent virtual agents with voice feedback could improve user's confidence in the agent's ability to perform tasks [37], and that voice types matter in participant's perception on the anthropomorphism of the virtual agents [16]. For this, a condition could be included where the non-human like agent i.e, pillar does not have a natural voice feedback. We will also look into reproducing the study with a different scenario from the art gallery to examine how the human-agent interaction could be adapted in another closed-space context.

Lastly, one could argue that it is not simply that the virtual agent occupies PS and the participant respects or impacts this space, but also that the PS of the participant himself/herself is likewise influenced. In other words, the matter of "Whose space is it?" cannot be immediately verified here though empirical work in both real and virtual social encounters have indicated that PS in social interaction is mutual and individuals' spaces coincide [30, 33, 71]. Future studies should examine the degree to which the participant allocates space to the virtual agent and whether this coincides with spatial preferences of the users themselves as this is critical for social AR experiences.

ACKNOWLEDGMENTS

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