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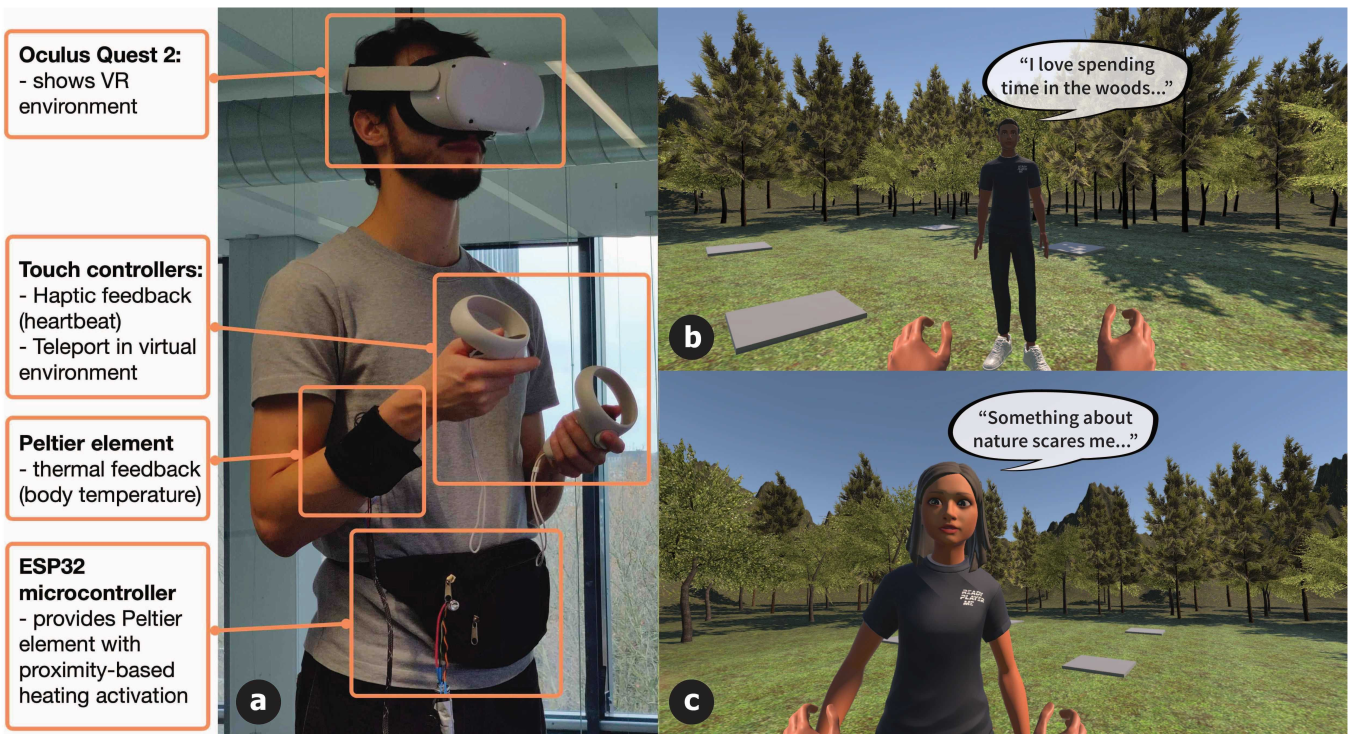

Figure 1: (a) Hardware components. (b) Participant's view of a trial with a male agent, telling a positive story at a large interpersonal distance, and (c) Trial with a female agent, telling a negative story at a short interpersonal distance.

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Abstract

Encounters with virtual agents currently lack the haptic viscerality of human contact. While digital biosignal communication can mediate such virtual social interactions, how artificial haptic biosignals influence users' personal space during Virtual Reality (VR) experiences is unknown. Designing vibrotactile heartbeats and thermally-actuated body temperature, we ran a within-subjects study (N=31) to investigate feedback (Thermal, Vibration, Thermal+Vibration, None) and agent stories (Negative, Neutral, Positive) on objective and subjective interpersonal distance (IPD), perceived arousal and comfort, presence, and post-experience responses. Findings showed that thermal feedback decreased objective but not subjective IPD, whereas vibrotactile heartbeats (signaling agent's closeness) increased both while heightening arousal and discomfort. Agents' stories did not affect IPD, arousal, or comfort. Our qualitative findings shed light on signal ambiguity and presence constructs within VR-based haptic stimulation. We contribute insights into artificial biosignals and their influence on VR proxemics, with cautionary considerations should the boundaries blur between physical and virtual touch.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices.*

Keywords

haptics, biosignals, proxemics, agents, virtual reality

ACM Reference Format:
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1 Introduction

In the real world, as we get physically closer to one another, we can sense more from each other's bodies. Close interpersonal distances, accompanied by communication using nonverbal cues, are hallmarks of proxemic behavior, which can result in greater warmth, attraction, immediacy, and positive attitudes [1, 2, 69]. Moreover, nonverbal cues are crucial for interpersonal communication, including communication of one's comfort and personal boundaries. Nonverbal signaling of boundaries reduces the risk of unintentional overstepping them and harassment. These necessitate boundaries that can prevent inappropriate touch or proxemic intrusions [2]. Recently, the proliferation of consumer head-mounted displays (HMDs) has made virtual reality (VR) systems an increasingly common means for social interactions [32, 82]. This enables meeting in a shared, immersive virtual environment [36, 60] and interacting with virtual representations of humans (avatars) and virtual agents. Naturally, close contact spatial encounters, whether in real or virtual worlds, lend themselves to the study of proxemics [29], which essentially looks at the amount of distance people are comfortable putting between themselves and others. Earlier work in proxemics has examined the equilibrium theory [4], which states that intimacy and interpersonal distance (IPD) vary together. Within VR, research has found that non-verbal cues including mutual gaze [7] and head gestures [8] can result in discomfort during such close encounters. While much work has focused on exploring proxemic behaviors across real [34, 105], VR [40, 70, 93, 110], and AR [38] environments, little is known about how haptic feedback may influence our proxemics perceptions and preferences during close contact virtual interactions.

To investigate the potential of communication of nonverbal cues through haptics, we explore how artificial biosignals (from temperature and heartbeats) function as novel nonverbal communication cues. Such cues do not necessarily convey explicit and interpretable social signals, as they are not ordinarily visible from outside the body [13], but when externalized can still be interpreted as meaningful signs of affective states (e.g., general wellbeing) [24]. To this end, we draw on the area of "interpersonal affective haptics" [20, 79, 84, 101, 103], which focuses on studying and designing haptic systems capable of eliciting, enhancing, or influencing human emotions through social interaction. Importantly, they can function as a means for setting physical [26] and interpersonal boundaries [2]. For the design of our haptic system, we chose two haptic modalities with established affective components, providing us with a solid base for an explorative study: thermal and vibrotactile displays. Thermal stimulation has association with human emotion [21, 79, 88, 113], where warm temperatures have been found to be comfortable and pleasant [47] and promote greater social proximity [41]. Similarly with haptic (touch) stimulation, where studies have shown associations with emotion and affective ratings [64, 87, 92], with the capacity to promote empathy [46].

While biosignal expressions through affective haptic have been shown to have positive effects on interpersonal communication and relations [24, 61, 72, 98], little is known about how we can breathe life into artificial agents by providing them with artificial biosignal-like signals. We set to investigate how we may design artificial biosignals of virtual agents expressed through haptics. Specifically, within our virtual proxemics context, we aim to examine whether such artificial biosignals influence users' IPDs during close encounters with virtual agents, and what it means for users' social VR experiences.

In this paper, we adopt a mixed-methods approach to design and evaluate haptic biosignal proxemics within human-agent interactions in VR. We ask: **(RQ1)** How can we design biosignals for virtual agents using proxemic haptics in a social VR setting? We focus on two biosignals: artificial heartbeat and body temperature. These biosignals lend themselves well for haptic communication as they have a sense of familiarity to them that makes them easier to comprehend than other physiological signals such as skin conductance or brain activity. For heartbeat: we used the Oculus Touch Controller's internal vibrotactile actuator to provide a heartbeat vibration pattern, that increases in intensity upon getting closer to the virtual agent. This design rationale reflects the heartbeat becoming more apparent the closer a user is in the proxemic zone of the virtual agent [29, 43], behaving as an artificial agent's nonverbal cue. For body temperature: we used Peltier elements as primary thermal actuators as part of a custom-built controller. Thermal feedback was given on the forearm with pre-defined temperature setpoints for each proxemic zone [29].

Given our prototype, we then ask: **(RQ2)** What are the effects of virtual agent haptic biosignals (vibrotactile heartbeats and thermally-actuated body temperature) on proxemic behavior and user experience? To answer this, we ran a controlled, within-subjects study (N=31) to investigate the effects of haptic feedback (None vs. Thermal vs. Vibration vs. Thermal+Vibration) on proxemic, i.e. on objective and subjective IPD. User experience was measured through perceived arousal, perceived comfort (trial-wise and overall comfort), cybersickness, presence, and preferences and interpretations as captured by interview responses. Social interaction was implemented through agents sharing valenced stories generated with

Large Language Models and text-to-speech synthesis. Providing virtual agents with valenced stories can enhance agent believability [76], enjoyment [23], and social presence [57]. While this was not the primary scope of this work, this formed an additional independent variable - story valence (Negative vs. Neutral vs. Positive), to help better understand what are the effects, if any, of virtual agent's story valence on proxemic behavior and user experience. While this goes beyond the central focus of our study, it provides additional exploratory observations that can strengthen the social interaction component of our study implementation.

Our key findings show (a) participants remained largely in the social zone (3.7-1.22 m away from the agent) regardless of haptic biosignals; however, while warm temperatures decreased objective IPD but not subjective IPD to a virtual agent, vibrotactile heartbeats increased both (b) vibrotactile heartbeats resulted in greater perceived arousal and lower comfort than with thermal or no haptic feedback (c) there were no differences in IPQ presence ratings across haptic feedback conditions, however, haptics influenced VR (dis-)embodiment experiences (d) the importance of multi-sensory integration and action-coupling, the inherent ambiguity of haptic biosignals, and how biosignals may risk imbuing (uncanny) anthropomorphic features onto virtual agents.

Our exploratory work offers two primary contributions: **(1)** We introduce the concept of haptic biosignal proxemics, and design vibrotactile heartbeats and thermally-actuated body temperature of virtual agents that respect proxemic IPD zones in a social VR setting **(2)** We provide empirically-backed insights and design considerations for haptic biosignal proxemics spanning IPD preferences to user experience factors, ultimately highlighting the promise and perils of future social VR interactions should virtual agents start (artificially) exhibiting haptically-actuated physiological reactions.

2 Related Work

The current work examines how interactions with virtual humans can unfold with additional communicative cues, like thermal and vibrotactile stimuli and multimodal biosignals. A Multimodal experience in virtual reality that incorporates various senses like haptics and touch can be powerful in fostering a sense of embodiment, i.e., a unique ownership and movement of one's virtual body that navigates across the virtual worlds [9]. Immersive realism in VR can be enhanced via affective haptics, like vibrotactile feedback, though this can be accompanied by feelings of nervousness, e.g., in a virtual crowd [102]. Thus, it becomes important to explore how virtual humans' use of shared space (proxemics) in VR is done in tandem with how they show artificial haptic biosignals, given that such combination of stimuli is a novel experience. In this section, we cover prior works of fields we touch on with our current work, namely: affective thermal and vibrotactile displays, how multimodal biosignals are represented, and spatio-relational boundaries with virtual humans.

2.1 Affective thermal and vibrotactile displays

Affective haptics [20, 84, 101, 103] is defined as a field that studies and designs haptic systems capable of eliciting, enhancing, or influencing human emotions. While affective haptics have been used to promote physiological relaxation [118], augment media experiences [79], and possibly to facilitate genuine feelings of connection [97], they have also been used for setting physical [26] and interpersonal boundaries [2]. Within research on thermal displays, prior investigations have shown that higher temperatures are generally characterized as comfortable and enjoyable [47], while also fostering social closeness [41]. Similarly, research has demonstrated an association between warmth and positive emotions, and coldness with negative emotions, when exposed to mild to moderate changes in temperature [21, 113]. Specifically, Salminen et al. found that a temperature change of 6°C, especially when transitioning to warmer conditions, was assessed as unpleasant, stimulating, and dominant, whereas a 4°C increase still evoked stimulation and dominance but was deemed pleasant [89]. For interpersonal warmth [3] however, findings are mixed: whereas earlier work in psychology showed that physical warmth promotes interpersonal warmth [19], this effect did not replicate [12, 108, 109], which warrants further scrutiny. Within the affective vibrotactile feedback, Yoo et al. [116] found that maintaining a constant vibration frequency on the hand could influence valence ratings. Conversely, Wilson and Brewster reported a contrary effect when assessing vibrations in isolation, with no discernible correlations to valence ratings when additionally introducing thermal stimuli [111]. Furthermore, Macdonald et al. [64] noted that vibrations with emotional resonance were generally perceived as positive, partially due to their familiarity. Seifi and MacLean determined that on-hand vibrations characterized by smooth and rhythmic patterns were perceived as positive, while rough and intense vibrations were viewed as more negative or alarming [92]. Finally, Yoo et al. [115] found that 200Hz vibrations were associated with higher valence ratings compared to the lower 70Hz frequency vibrations when combined with thermal stimuli at temperatures of 20°C, 30°C, and 40°C. Lastly, Jones and Singhal [45] discovered that warming the skin affected the ability to discern vibration patterns. Given our objective of designing artificial haptic biosignals, we draw on these prior works for designing vibrotactile heartbeats and thermally-actuated body temperature. Grounded on research that shows association of social and physical closeness with felt physical warmth, we map proximity to thermal actuation and design this according to known comfortable temperature actuation steps of Salminen et al. [89]. Similarly, we represented heartbeat as a rhythmical vibration as prior work of Seifi and MacLean indicates this to be a comfortable actuation [92]. Following Jones and Singhal [45], we combine both actuations to increase the perception of vibrotactile stimuli. Additionally, since our focus is on proxemics and haptics, we delve into new territory as we represent these biosignals using virtual distance-dependent haptic actuation.

2.2 Multimodal biosignal representation and communication

Much work has been done on multimodal representation of biosignals [14, 35, 74, 75], and the communicative benefits of sharing biosignals [24, 59, 61, 72, 98]. Indeed, biosignals as a nonverbal cue can augment feelings of connectedness, empathy, intimacy, affective interdependence, and sharing of an experience between people. However, they can also be inherently ambiguous when presented as a social cue [37]. In WearBEAT [71], Min &Nam found that close friends sharing vibrotactile heartbeats indicated their prior relation to be important for creating connectedness. Lee et al. showed with Empatalk [58] that vibrotactile heartbeats enhance engagement in the conversation and increases the feeling of co-presence in a video chat system. Morris et al. developed EmbER [74] that allows sending haptic or audio heart rate and breathing, and showed that devices capable of transferring interoceptive sensations, especially below conscious perception, could facilitate feelings of connectedness. Desnoyers et al [17] showed that visualizing and sonifying a heart inside another's ephemeral avatar draws people closer, instilling the desire to touch the other's heart. For temperature communication, the Baroesque Barometric Skirt [5] aims to facilitate conversation by using the environment temperature and its wearer's body temperature to change colored LEDs woven into the fabric. AMIA [18], an augmented version of the dice game Mia, portrays the change in body temperature as a colored icon on a hat only visible to the other players. With respect to proxemics, Janssen et al. [43] showed that heartbeat perception influences social behavior in a similar manner to more common signals such as gaze and interpersonal distance, however is dependent on the heartbeat being attributed to the conversation partner. Kuling et al. [55] also found that hearing someone's heartbeat increases the interpersonal distance that is kept, and explain this finding as a compensation strategy for the increased feeling of intimacy. Closer to our work, Hecquard et al. [35] recently investigated physiologically-based affective haptic interfaces (compression belt and a vibrator) to simulate breathing and heart rate of a virtual agent presenter. By comparing sympathetic haptic rendering with an indifferent one for stress communication, they found that sympathetic haptic feedback is preferred, as it can enhance empathy and perceived connection to the agent. While the aforementioned works highlight the importance of multimodal representation of biosignals for communicative functions, little is known how imbuing virtual agents with artificial haptic heartbeats and thermally-actuated body temperature influences proxemic behavior in VR.

2.3 Virtual humans and proxemics

By investigating distance-dependent haptic biosignal representations as a nonverbal communication cue, we naturally find ourselves in the field of proxemics [29] – which concerns the study of communication via interpersonal space and utilizing this space to regulate interaction. Hall defined four proxemic zones of interpersonal space: (1) Public: >3.70m, (2) Social: 1.22m-3.70m, (3) Personal: 0.46m-1.22m, and (4) Intimate: <0.46m. Within this continuum, haptic behaviors are of vital influence in the communication of power, control, privacy, and physical boundaries [2]. When invading someone's comfortable interpersonal space, most people will attempt to re-establish this to comfortable levels through changing body orientation or retreating [2]. Feelings of discomfort with regards to IPD are found to be anisotropic, where intrusion is experienced with more discomfort than extrusion [105]. Several studies have explored proxemic interactions in virtual spaces. Prior work has tested equilibrium theory [4], where intimacy and interpersonal distance (IPD) vary together. They found that non-verbal cues including mutual gaze [7] and head gestures [8], can result in discomfort in such close encounters, where this is reflected physiologically [107]. Williamson et al. [110] studied proxemic behavior in a virtual workshop, and found that small groups of people in an enclosed space stand in each other's personal and social IPD zone, whereas larger groups in an open space stay in the public IPD zone. Mello et al. [70] observed that effects of virtual agent's gaze on IPD are mediated by user's levels of social anxiety. Indeed, as IPD norms vary across users, feelings of harassment in the form of invading personal space can surface in social VR settings [25]. Relatedly, while males usually keep larger distances to males in comparison to females in real life [34, 40], Hecht et al. did not find this with virtual male agents [34]. However, people do tend to accept closer IPDs when being approached by a human-like agent than by a robot-looking agent [50]. When being approached by virtual agents [62] or a standing agent reacting to a participants' presence at small IPDs [54], skin conductance levels increase when being closer to the agent [107]. Huang et al. [38], in their human-agent AR setup, observed heightened skin conductance levels only when participants were asked to walk through the virtual agents. The aforementioned helps ground the design of the interaction with the virtual agent with respect to proxemic behaviors. Given the affective component for our agent interactions, we modeled our virtual agents with varying valenced stories, as these are purported to enhance agent believability [76], enjoyment [23], and social presence [57]. With these virtual agents, we aimed to explore how such proxemic behaviors vary as a function of haptic biosignals imbued on an embodied conversation agent in VR.

3 Methods

3.1 Study design

Our study is a 4 (IV1: Haptic Feedback: None vs. Thermal vs. Vibration vs. Thermal+Vibration) x 3 (IV2: Agent Story: Negative vs. Neutral vs. Positive) within-subject design, tested in a controlled, virtual environment. Our study consisted of 24 trials divided into four blocks (per feedback type), where each block contains six trials with two representative agent stories: 2 negative, 2 neutral, 2 positive. Haptic feedback conditions were counterbalanced according to a Latin square design, where within a block the six trials were randomized. We randomized the order of the agent gender, ensuring a 50/50 ratio, given that prior work has shown differing stereotypical attributions to gendered agents [85], modulated IPD with respect to agents' perceived gender in AR [38], and that people preferred greater distances if touched by a robot agent [50]. This was used primarily as a control, given agent gender was not the focus of our study.

In this study, we include both measures that are key to our research focus and additional measures to further explore relevant factors that could inform future research, given the novelty of the setup of the study. Key measures include the objective distance and subjective distance rating to assess the stimuli's impact on IPD. Additional measures include, for example, comfort and arousal to assess the perception of the stimuli, IPQ and SSQ to assess the VR design, and lastly to explore if the agents' stories impact the VR experience. All measures include: (a) Trial duration (b) Objective distance to agent (through position logging) (c) Subjective distance ratings (trial-wise) (d) Arousal ratings (trial-wise) (e) Stimulation comfort ratings (trial-wise) (f) IPQ Presence questionnaire [90] (g)

Figure 2: (a) Female agent (b) Male agent (c) Example arousal post-trial question

Simulator Sickness Questionnaire (SSQ) [48] (h) Comfort Rating Scale (CRS) [51, 52]. Measures (a)-(b) were logged automatically each second, where (a) the time elapsed since starting the trial and (b) the actual distance the participant kept from the agent. Measures (c)-(e) took place within the VR forest environment after each trial through an embedded 7-point Likert-scale panel, allowing participants to stay immersed in the VR experience [83]. Subjective distance scale (*"I wanted to maintain a sense of distance between us"*), an item taken from Nowak et al's social presence questionnaire [77], ranged from strongly disagree (1) to strongly agree (7). Perceived self-arousal scale (*"I felt excited during this last interaction"*) with example panel shown in Fig. 2 ranged from very calm (1) to very excited (7). Haptic feedback comfort (*"I found the sensation of haptic stimulation (thermal, vibration feedback) to be comfortable"*) ranged from very uncomfortable (1) to very comfortable (7), with an additional response of N/A for trials with no stimulation. Cronbach's α for items (c)-(e)=0.54.

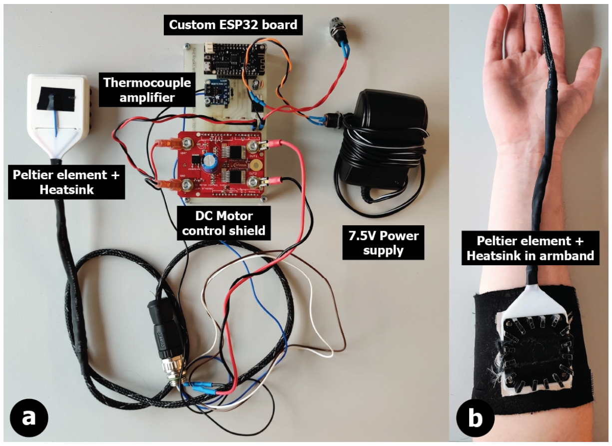
Measure (f) IPQ took place within VR after each block to assess the level of presence and immersion per feedback condition, again using the embedded 7-point Likert-scale panel for all 14 questions (Cronbach's α=0.38). We chose the standardized SSQ [48] to measure the level of motion sickness on a scale from 1 (none) to 4 (severe) before (Cronbach's α=0.83) and after (Cronbach's α=0.9). Finally, we used CRS to assess overall perceived comfort of using our prototype (Cronbach's α=0.8). Qualitative data were gathered through a semi-structured interview outside of VR after the participant finished all 24 trials. The consensually audio-recorded interviews asked participants about their overall study impression, their perceptions of the VR environment, the vibrotactile and thermal feedback of agent biosignals, the agents and their stories, proxemics, and provocations regarding further use cases. The interview guide with all questions can be found in Supplementary Material D. Our study followed strict guidelines from our institute's ethics and data protection committee, including any prevailing cleanliness (cf., COVID-19) regulations.

3.2 Hardware and software setup

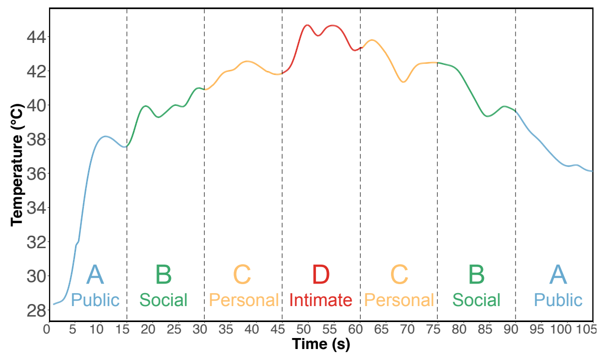
3.2.1 Proxemic thermal feedback. We used Peltier elements (TEC1-12706 thermoelectric modules) as primary thermal actuators, given their capabilities in providing fast changes in temperature for generating cool or warm stimuli [21, 30, 78, 81]. Following prior work [21, 78], we forego the PID controller when the Peltier element reaches a setpoint, and instead apply a constant maximum output value to drive the element until it reaches the target temperature. Since a higher output value necessitates a higher current, we use a DC motor driver. To avoid the increased heat generated due to resistance, we use only 7.5V. Our thermal display system components (Fig. 3(a)) include a custom ESP32 microcontroller, a 3.3V regulator, Adafruit 1-Wire Thermocouple Amplifier (MAX31850K)[1], a K-type thermocouple, Infineon DC Motor Control Shield BTN8982TA[2], and a Peltier element attached to a heat sink. Power values, indicating the direction and intensity of temperature changes, are communicated from the HMD to the ESP32 over WiFi with a 115200 baud rate.

For proxemics-driven thermal stimulation, determining which value to communicate depends on the target and current temperature of the Peltier element, as well as the distance to the agent. Based on Hall's [29] proxemics zones, we designed the temperature zones in virtual meters, which are perceived similar to real-life meters [42]: (a) Public zone, further than 3.70 m away: 36°C (b) Social zone, between 3.70 and 1.22 m away: 40°C (c) Personal zone, between 1.22 and 0.46 m away: 42°C (d) Intimate zone, within 0.46 m distance: 44°C. Based on on-body wearability guidelines [117], acceptable areas for social touch with acquaintances and strangers [100], we chose the inside of the forearm, given suitability for local warm stimuli [63]. The local skin temperature on the forearm typically sits at room temperature of around 34°C [99]. The temperature for the public zone was therefore set to 36 °C to only be slightly noticeable. When entering the social zone, the temperature increases to 40°C to clearly differentiate in stimuli between the zones. Following earlier work on thermal displays [89], this change of 4°C is regarded as dominant but pleasant still, whereas an increase of 6°C would be regarded as unpleasant. When entering the personal and intimate zones, the temperature will again increase by 2°C per zone, respectively to 42°C and 44°C, to avoid the maximum temperature becoming too hot. An armband made of stretchy neoprene, with a square cutout for the Peltier, holds the Peltier in place. A thin piece of silk fabric with thermal conductivity ranging between 0.08-0.1 (W/mK) was placed between the skin and the Peltier element, to ensure stimuli are more comfortable than direct skin stimulation [31]. Although this might increase the detection time of the thermal stimuli, this does not influence our study designs, since trials are not time-critically brief in duration (cf., voice message stimuli [21]). The armband is worn throughout the entire study, avoiding interruptions of taking it off and putting it back on, and the Peltier turns off during trials without thermal stimulation. With our parameters, and given our VR proxemics setting, we show our real-time temperature plot (with smoothing spline function; spar=0.5) in simulated

[1]https://learn.adafruit.com/adafruit-1-wire-thermocouple-amplifier-max31850k/wiring-and-test
[2]https://www.infineon.com/cms/en/product/evaluation-boards/dc-motorcontr_btn8982/



(a) Thermal display system components, showing (a) Peltier element with heatsink and accompanying circuit components, and (b) armband with Peltier element embedded.



(b) Real-time temperature plot across proxemic zones

Figure 3

15-second interval buckets, crossing all proxemic zones back and forth (Fig. 3(b)).

3.2.2 Vibrotactile feedback. We used the third iteration of the Oculus Touch controller's internal vibration actuator to provide vibrotactile stimulation on only one controller. This was done to avoid overstimulation, specifically when placed on the same site [65]. Custom vibration patterns were composed through haptic impulse modulation of amplitude and frequency within Unity. An animation curve in Unity shaped like an electrocardiogram (ECG) graph was used to provide a representative series of amplitudes that simulate a heartbeat pattern. Similar to prior work by Lee et al. [59], our focus here was on a simulated resting heartbeat pattern with a beat every 0.8 seconds, translating to 75 BPM. This is within the average human heart rate [6]. The heartbeat vibration pattern was empirically assessed for accuracy, intensity, and comfort by the first author in multiple iterations of the design. During a study trial, the closer a participant approached the agent, the higher the felt intensity of the heartbeat vibration. Drawing again on Hall's proxemics theory [29], the switching point between public and social distance is 3.70m, where the vibration intensity curve becomes more noticeable from a distance closer than 3.70m, and increases linearly as the participant comes closer. During the trial, the intensity of the vibration is continuously calculated using a multiplication of the maximum vibration intensity (0.6 of the maximum motor power), the linear distance factor (0.0 at 5m and 1.0 at 0m), and the amplitude of the ECG curve at that moment (1 at maximum height of the QRS Complex[3] R wave and 0 during the TP segment).

3.2.3 Virtual environment, agent design, and user interaction. Following Marcolin et al.'s [66] philosophy on designing experiment-focused VR environments, we chose a forest clearing in daytime setting, that is neutral in valence, low in arousal, and high in dominance. The setup[4] was implemented in Unity[5] using the Universal Render Pipeline to ensure high-quality graphics and the OpenXR Plugin that simplifies AR/VR development. The Meta Quest 2 HMD was used for displaying the scenes because of its ability to work wirelessly, with a reasonable FOV (85°-97°) and per eye resolution (1832 x 1920 pixels). The agents were created with the Ready Player Me platform[6], using the standard posture and face, and agents wearing basic black clothing and white shoes. Thereafter, the agents were animated using the Adobe Mixamo talking animation[7]. The self-avatar was coupled to the main camera and the controllers in Unity using a custom animation Rig[8]. Despite previous work showing relationships between IPD and avatar height [80], we kept the default agent height at 180cm, considering that the self avatar view is set to 180cm, and that this was not the focus of this work. Participants' self-avatars consisted of an upper body and gender-neutral arms (cf., [91]) and was kept the same throughout the full study. The rest of the scene was built using Unity's free asset packages[9]. Supplementary Material A shows a video of the environment and avatar-agent interaction.

The virtual environment consisted of a grid of 25 equidistant teleportation mats (see Fig. 1), with 2.5 meters between each in a visible yet non-distracting gray hue, matching the forest clearing area where the agents stood. We enabled participants to get closer to the agent using teleportation, a comfortable and minimally nauseating locomotion technique [11]. This enabled participants to initially traverse larger distances, and only afterward walk within

[3]https://en.wikipedia.org/wiki/QRS_complex

[4]https://github.com/SimoneID/AvatarBiosignals
[5]https://unity.com/
[6]https://readyplayer.me/
[7]https://www.mixamo.com/
[8]https://docs.unity3d.com/Packages/com.unity.animation.rigging@1.1/manual/RiggingWorkflow.html
[9]https://assetstore.unity.com/; Trees: Mobile Tree Package by Laxer; Path Material: Yughues Free Ground Materials by Nobiax / Yughues; Grass: VIS - PBR Grass Texture by VIS Games; Bird sounds: 44.1 General Library (Free Sample Pack) by InspectorJ Sound Effects

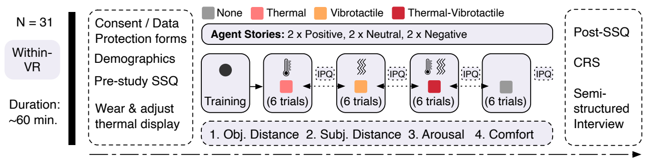


Figure 4: Study procedure. From start to finish: filling in of pre-study forms and explanation of the study procedure, a training environment in VR, the study with 24 trials in four blocks of six trials (block order in Latin square design, trial story within block in randomized order, IPQ Presence questionnaire between each block in VR), filling in post-study forms and exit semi-structured interview.

the experiment area (2.5m x 2.5m) if they so chose. We randomized the starting distance from the agent in each trial, where a participant was always spawned in the corner of the clearing just outside of the 10m x 10m grid. Agents were spawned randomly within the grid[10]. As the participant switched position, whether through teleportation or walking, the thermal and vibrotactile stimuli changed in accordance with the proxemic zone they were in.

3.2.4 Agent story valence and speech synthesis. For the agent stories, we drew on advances (in Dec 2022) in text-to-text language models, and on text-to-speech synthesis to provide the agent with a representative AI voice and monologue (story) that matches their gender appearance. For the negative and positive valence stories, we used OpenAI's GPT-3[11] language model with the following base language prompt: "nature, forest, <positive | negative>, experience, conversation". To assess the text sentiment for positive or negative valence, we used a sentiment analyzer from Hugging Face with a default English sentiment analysis model[12], which validated that these had the desired valence. For the neutral stories, we selected a relevant paragraph from Wikipedia entries on for example: Nature, Forest, Leaf, Tree, Ecosystem, etc. As a final validity check, two authors went through each of the generated stories to ensure that these stories are representative of what an agent in a social VR environment would say, with the correct sentiment. Lastly, all stories were synthesized into speech using Google AI's text-to-speech engine[13], where two authors empirically determined the following gender parameters for female and male voices to help ensure the voices sound plausible and match the agent appearance, respectively: Female voice: -F - 0.96x speed; Male voice: -I - 0.93x speed. Agent stories were approximately one minute in duration. All story transcripts with indicated valence and associated audio files are provided in Supplementary Material B. For consistency throughout the experiment, and avoid introducing yet another variable in the study design, the volume of the HMD was set to 75%. The lead author and a pilot participant determined this empirically by measuring sound audibility across a sample of 24 trials, where sound was audible at a range up until approximately 8m (M= 8.31).

[10]Agent location is randomly determined using [active agent object].transform.position = new Vector3(Random.Range(0, 10), 0, Random.Range(-10, 0))
[11]https://en.wikipedia.org/wiki/GPT-3
[12]DistilBERT base uncased finetuned SST-2; https://huggingface.co/distilbert-base-uncased-finetuned-sst-2-english
[13]https://cloud.google.com/text-to-speech

3.3 Study procedure

Our study procedure is shown in Fig. 4, where a session lasted approximately 60 minutes. Participants first read and signed the informed consent form, and filled in a demographics form as well as a pre-study Simulator Sickness Questionnaire (SSQ). Then a verbal explanation about the study was given by the experimenter, which included: (1) explaining which parts of the prototype would be vibrating or heating up (note: this explanation did not include what the purpose or meaning of the stimuli are), (2) how to operate the Oculus Touch controllers for teleportation and selecting items in VR, and (3) explaining the task: "Find a comfortable distance from the agent telling a story". Afterward, the participant was equipped with the thermal prototype and the HMD to ensure comfort. Audio was provided through the HMD's speakers (set at 75%). A VR training environment was provided to allow participants to familiarize themselves with the controls for teleportation and menu selection. After training, participants proceeded to the main study trials, consisting of 24 trials divided into four feedback conditions. For each trial, the participant pressed a dedicated button on the controller to confirm they had found a comfortable distance. This could be done while the agent was still speaking or at the end of the story; participants were however encouraged to stay in their perceived comfortable position for a bit before confirming to make sure they sufficiently experienced the stimuli matching their position. Previous studies used delays between 10 sec [112] to two minutes [31] for thermal re-adaptation, to avoid adaptation effects of the skin [44]. Given participants provided ratings after each trial, this allowed for a cooling period. Participants were provided with optional short breaks in between the study blocks. At the end of the study, participants filled in the post-study SSQ form and CRS form. Lastly, participants underwent a semi-structured interview and were rewarded with a €/$10 voucher for participating.

3.3.1 Participants. 31 participants [14] (16f, 14m, 1 non-binary) were recruited, with the following age distribution: eight 18-24, sixteen 25-34, two 35-44, three 45-54, and two >54 years old were recruited. Participants were recruited primarily from our and neighboring institutes. In total 11 students, 14 researchers, and 6 other deployment positions composed the participant group. 83.9% reported having used an HMD-based VR device at least once, whereas only 25.8% reported having used a social VR platform at least once. Only three participants reported owning a VR device.

4 Results

4.1 Quantitative results

We analyzed the combined effects of Haptic Feedback and Agent Story Valence on participants' time spent, mean objective distance to the agent, their subjective distance ratings, their perceived arousal, and comfort ratings, by fitting a full linear mixed-effects model on each dataset. Since our data distribution for each was not normal, we applied the aligned rank transform prior to fitting [114]. Post-hoc contrast tests were performed using ART-C [22]. Analysis of deviance table for all response variables is shown in Table 1.

[14]For effect size f=0.25 under α=0.05 and power (1-β)=0.95, with 24 repeated measurements within factors, one would need minimum 12 participants.

Response Variable	Factor	F	df	p	η_p^2
Mean Obj. Distance	**Feedback**	27.1	3	< .001**	0.10
	Story	0.14	2	0.87	0
	Feedback x Story	0.61	6	0.72	0.01
Subj. Distance	**Feedback**	59.2	3	< .001**	0.20
	Story	0.41	2	0.66	0
	Feedback x Story	0.38	6	0.89	0
Arousal	**Feedback**	32.7	3	< .001**	0.12
	Story	1.07	2	0.34	0
	Feedback x Story	0.57	6	0.76	0
Comfort	**Feedback**	136.1	3	< .001**	0.37
	Story	0.0	2	0.99	0
	Feedback x Story	1.09	6	0.37	0.01

Table 1: Analysis of deviance on the full mixed-effects model for mean objective distance using Aligned Rank Transformed data.

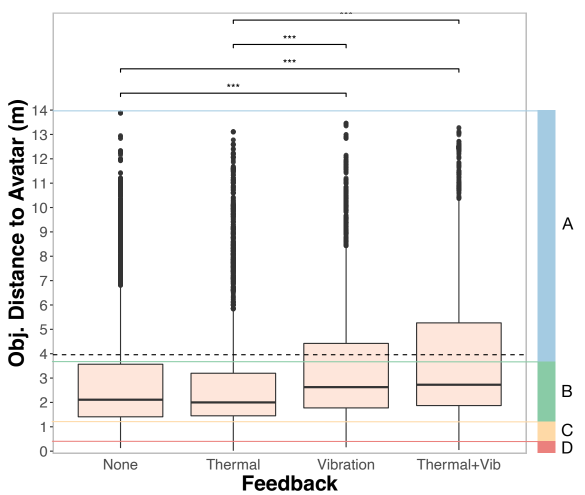


Figure 5: Objective distance to agent per feedback condition. Proxemic zones shown on the right: (A) Public: >3.70m, (B) Social: 1.22m-3.70m, (C) Personal: 0.46m-1.22m, and (D) Intimate: <0.46m.

4.1.1 Mean trial duration per feedback condition. We first looked at how much time participants spent in each Haptic Feedback condition, as a quick measure to assess abandonment of the experience due to the the type of stimulation delivered. Average time spent per trial across Feedback conditions (in seconds) were: None (M=36.31, SD=21.49), Thermal (M=35.42, SD=19.79), Vibrotactile (M=33.95, SD=20.13), Vib-Thermal (M=37.46, SD=28.31). We further analyzed the effects of Haptic Feedback on participants' time spent in each condition by fitting a full linear mixed-effects model, since our data distribution for each was not normal. We applied the aligned rank transform prior to fitting, however found no significant effects of any of our feedback conditions on trial time.

4.1.2 Mean objective distance to agent. Objective distance to virtual agent across participants for each Feedback condition is shown as boxplots in Fig. 5. The dashed line shows the mean distance across feedback conditions, and lines with asterisks indicate pairwise (Bonferroni corrected) significance. Given that participants teleported closer to the agent, for analysis we filtered the distance data for nearby interaction, setting a cutoff distance of < 6m. This was determined empirically based on Fig. 5, where prior work set public IPD (far) at 8m [110]. Moreover, since the audibility threshold was approximately 8m, this was a reasonable cutoff distance to ensure no confounds in locomotion (and subsequently proxemic) behavior. We then compute the mean distance across each participant for each feedback condition, and use this dataset for subsequent analysis.

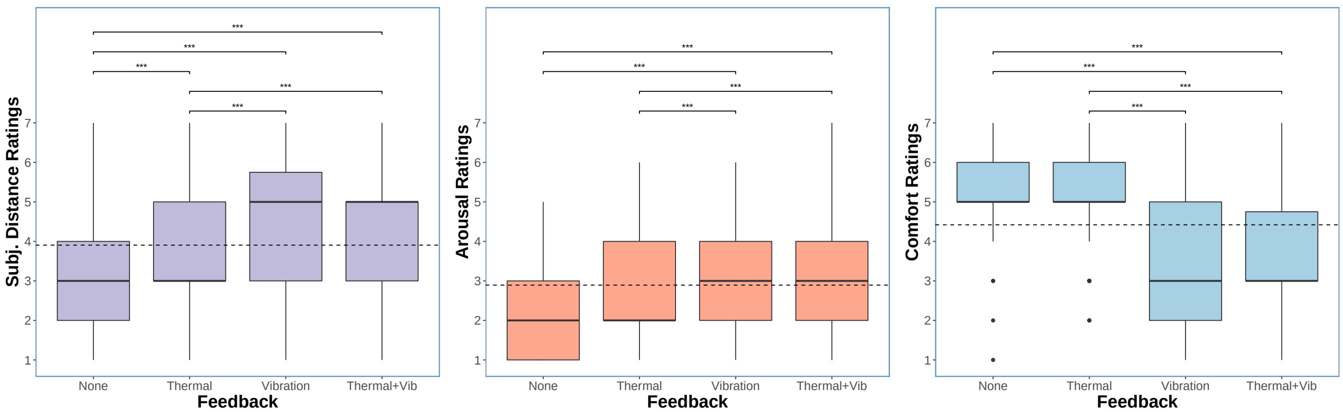
From Table 1 (Mean Obj. Distance), a full mixed-effects model showed significance for only Feedback ($p < 0.001$). No significant interaction effects were found. Contrast tests for the main effect of Feedback revealed significant differences between all levels ($p < 0.001$), except between None and Thermal ($p = .93$), and between Vibrotactile and Vib-Thermal ($p = .51$). This indicates that participants' mean actual distance to the virtual agent did not vary accordingly between no feedback and thermal feedback, where the thermal feedback additionally did draw participants closer to the agent when paired with a vibrotactile heartbeat. Full contrasts tests tables are shown in Supplementary Material C, where the negative effect sizes show that introducing vibrotactile feedback increases users' distance to the agent, compared with thermal feedback alone.

4.1.3 Subjective distance. Subjective distance ratings to the virtual agent across participants for each Feedback condition is shown as boxplots in Fig. 6(a). The dashed line shows the mean subjective distance ratings across feedback conditions, and lines with asterisks indicate pairwise (Bonferroni corrected) significance.

From Table 1 (Subj. Distance), a full mixed-effects model showed significance for only Feedback ($p < 0.001$). No significant interaction effects were found. Contrast tests for the main effect of Feedback revealed significant differences between all levels ($p < 0.05$), except between Vibrotactile and Vib-Thermal ($p = .83$). This indicates that participants' subjective distance ratings to the virtual agent did not vary accordingly between including and not including thermal feedback to the vibrotactile heartbeat feedback condition. Full contrasts tests tables are shown in Supplementary Material C, where the negative effect sizes show that introducing vibrotactile feedback increases users' subjective distance preferences to the agent, and additionally the inclusion of thermal feedback increased participants' distance preferences.

4.1.4 Perceived arousal. Perceived arousal ratings across participants for each Feedback condition are shown as boxplots in Fig. 6(b). The dashed line shows the mean arousal ratings across feedback conditions, and lines with asterisks indicate pairwise (Bonferroni corrected) significance.

From Table 1 (Arousal), a full mixed-effects model showed significance for only Feedback ($p < 0.001$). No significant interaction effects were found. Contrast tests for the main effect of Feedback revealed significant differences between all levels ($p < 0.05$), except between None and Thermal ($p = .63$), and between Vibrotactile and Vib-Thermal ($p = .99$). This indicates that participants' perceived arousal ratings did not vary accordingly between no feedback and thermal feedback. This additionally suggests that thermal feedback



(a) Subjective distance ratings (b) Perceived arousal ratings (c) Perceived comfort ratings

Figure 6: Plots on the post-trial question ratings per feedback condition.

did not add sufficient stimulation to the vibrotactile heartbeat condition to distinguish it from vibrotactile feedback only, with respect to perceived arousal ratings. Full contrasts tests tables are shown in Supplementary Material C, where similarly to the mean objective distance data, the negative effect sizes show that introducing vibrotactile feedback increases users' perceived arousal ratings, by contrast to thermal stimulation alone.

4.1.5 Perceived comfort. Perceived comfort ratings across participants for each Feedback condition are shown as boxplots in Fig. 6(c). The dashed line shows the mean comfort ratings across feedback conditions, and lines with asterisks indicate pairwise (Bonferroni corrected) significance. Note that since we had N/A as an option for the perceived stimulation comfort in the None condition, these N/A responses were assigned a value of 5, indicating comfort. This was based on the fact that 59 non-N/A responses had a median comfort of 5 (mean=4.92), which indicates that no stimulation is comfortable (but not extremely comfortable to be a 6 or 7). By making this assumption and computing the comfort level for the no stimulation condition, it allows having a baseline reference for the stimulation modes.

From Table 1 (Comfort), a full mixed-effects model showed significance for only Feedback ($p < 0.001$). No significant interaction effects were found. Contrast tests for the main effect of Feedback revealed significant differences between all levels ($p < 0.05$), except between None and Thermal ($p = .24$), and between Vibrotactile and Vib-Thermal ($p = .75$). This indicates that participants' perceived comfort ratings did not vary accordingly between no feedback and thermal feedback. This additionally shows that thermal feedback did not add sufficient stimulation to increase comfort when vibrotactile heartbeat stimulation was delivered. Full contrasts tests tables are shown in Supplementary Material C, where here we find positive effect sizes that show that introducing vibrotactile feedback consistently decreases users' perceived comfort ratings, by contrast to thermal or no stimulation.

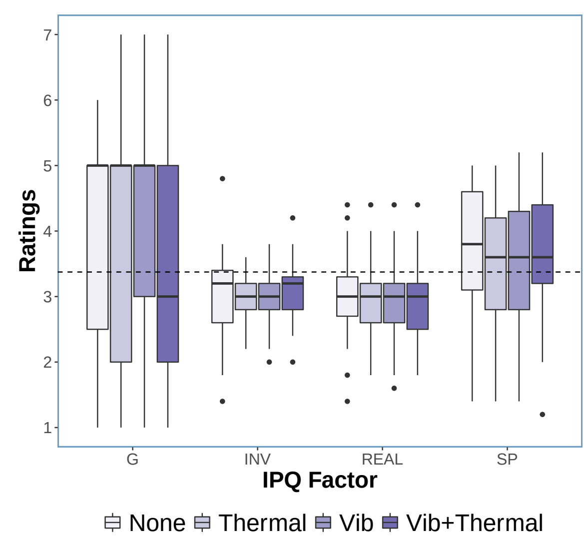


Figure 7: IPQ factors per condition

4.1.6 IPQ presence ratings. To assess users' reported sense of presence during their VR experience, we analyzed the per block IPQ questionnaire responses across each Feedback conditions and across each presence factor within IPQ. Sum of scores across participants for each factor of IPQ and across Feedback conditions is shown as boxplots in Fig. 7. We then analyzed the effects of Haptic Feedback on participants' IPQ factor scores by fitting a full linear mixed-effects model, since our data distribution for each was not normal. Here again we applied the aligned rank transform prior to fitting. We found no significant effects of any of our feedback conditions on any of the IPQ factors.

4.1.7 Comfort Rating Scale (CRS). For each CRS subscale [51, 52], the lower the score, the more it contributes to overall subjective comfort. Results for each factor are: Emotion (Md=1, IQR=4), Attachment (Md=14, IQR=5.5), Harm (Md=3, IQR=7.5), Perceived Change (Md=11, IQR=7.5), Movement (Md=14, IQR=7), Anxiety (Md=4, IQR=11).

4.1.8 Motion sickness in VR. We tested whether our VR study had an influence on participants' reported motion sickness as measured with SSQ. A Wilcoxon signed-rank test (suitable for non-normal data) showed significant differences between pre-study (Md=0.13, IQR=0.31) and post-study SSQ (Md=0.38, IQR=0.47) scores (Z=-4.22, $p<0.001$, r=-0.76), indicating that our VR experience did result in increased reported motion sickness.

4.2 Qualitative results

We analyzed the data with inductive thematic analysis [10, 15] from an interpretive standpoint [95], which means that we aim for a discussion-led, collaborative approach. To increase rigor, we did count how often a statement was said, however, the interview was semi-structured in nature thus it cannot simply be said that participants who did not say the statement would disagree as the specific topic might not have come up. To reach saturation [95], three authors separately analyzed the qualitative data before meeting with all authors to discuss our analysis. First, we coded it according to evoked topics. Then within each topic, we analyzed emerging themes. Participants are labeled P0-P30. We find a rich set of reflections from participants on what haptics and biosignals in VR felt like, what they represented, and what communicative functions they served.

4.2.1 Ambiguity of haptic biosignals. As feeling the vibration when sensing one's heartbeat is not a typical real-life experience, this peculiar interaction resulted in participants attributing a multitude of meanings to the sensation. For seven participants, the vibration pattern clearly represented a heartbeat: *"It crossed my mind for a while with the vibration because it has like a pulse like it was coming tun-tun-tun-tun. It crossed my mind that it could be heart rate"* [P24]. For four others, the pattern reminded them of the more familiar smartphone buzzing: *"I hadn't felt that because normally you have a heartbeat of say one per second and I just felt this like the phone"* [P19]. Hence, what people expect to be a rhythm or resonance of a heartbeat can sometimes drastically vary, hinting at the **inherent ambiguity of expressed biosignals**. Further, several participants were confused about the continuous stimulation of the vibration, two felt that in a more game-like fashion, it should be responsive to specific actions: *"It must be more representative of the actions. Like, I don't know, when you high five with somebody and then you feel vibration or something"* [P29]. In these cases, it did not merge into a single perception of others' heartbeats through haptic vibrations. Eight others speculated how it might relate to their real-world experience: *"It didn't feel as part of the person. It was more or less two separate things which I needed to perceive at the same time. Usually, I also don't feel other people's heartbeats whenever I stand next to them"* [P2]. Ten participants ascribed **emotional or valence attributes to the agent through the haptic signal**: *"The lower heartbeat, of course, is a symbol of being calm and cool and calmed down, but the higher shows how stimulated you are"* [P30]. Thus, vibration may be perceived as an agitation of the agent: *"...in real life we do that all the time and you really notice quite quickly when somebody feels uncomfortable"* [P7]. Conversely, P13 interpreted this excitation with a positive valence: *"If the vibration is stronger, maybe it denotes people who are telling the story are more excited"* [P13].

Regarding temperature, six participants mentioned they do not think that it could be indicative of emotions of the agent: *"Like body temperature doesn't change much depending on your feelings, right? But heart rate changes...you can be excited or you can be calm"* [P20]. Instead, temperature was sometimes interpreted as valence of the environment or situation: *"If it's supposed to be like, stressful, maybe you could get warm temperatures and if it's like scary, cold"* [P26]. Indeed, participants could **attribute the thermal sensation to the signal from either the agent or the environment**. In both cases, it can be perceived as an indication of the physical aspect, e.g., warmth of the room or a person, or collision with a physically solid body, or more metaphorically as a mood of the environment: *"As soon as the sun shines or comes through and you feel warmth...I would indeed see it more as an environmental factor, not related to that person, to that avatar"* [P16]. While such **action-coupling**, **unified sensory integration**, and **clear haptic valence attribution** could perhaps provide a more immediate meaning to the signals, it also constrains the exploratory nature of what haptic biosignals could signify.

4.2.2 Agent stories, proxemics, and haptic stimulation effects. Seven participants mentioned they were drawn closer to the agent if the story captivated them or that when the agent's stories were impersonal in nature (i.e., neutral), then they stood further away: *"I thought they were like some kind of, you know, a guide or, you know, like less personal. Maybe they were like an instructor, maybe I will stand further away because I feel like they're not talking directly to me"* [P25]. Despite any influence of story valence, the haptic modalities tested gave different meanings or emphasis to the stories. For example, five participants felt they were unable to focus on the stories because the haptic stimuli were uncomfortable: *"Whenever there was vibration, I felt that I was more triggered, and I was more annoyed by the person* [agent]. *So, with the vibration, I was even more thinking, could you please shut up?"* [P8]. Further, if participants were too focused on the agent and its stories, they did not feel the various cues we introduced: *"Sometimes, when asked, how did you experience the vibration and the warmth, I thought 'Did I feel something, I don't remember?' Sometimes I am so focused on that person that I just completely forget about it. So then it was where I thought I had felt something"* [P6]. This suggests that until people were made to consciously check in on their felt experience, they did not actively keep track of them, suggesting a **haptic overriding effect**. The foregoing highlights the intricate relation between space, movement, and multimodal haptic stimuli, and how they attributed meaning to the signals when interacting with virtual agents.

4.2.3 Qualities of the haptic stimulation. The vibration was more noticeable than the thermal stimulation, with three participants not perceiving the heat change at all and six stating the heat change is subtle so if they did not focus on it they "couldn't really detect when it was turning on or engaging" [P11]. Thirteen participants mentioned finding the constant vibration annoying, although seven also described it as being comforting when they keep at certain distances: *"It felt, really soothing I would say, like, it felt nice on my hand"* [P22]. The heat was often unnoticed, but when it was detected, participants typically would find that it *"felt nice"*[P22] and may feel psychologically comforting: *"I'm not sure if I want to feel other people's heart rate or biosignals. Maybe warmth might help me feel a bit more, not comfortable, but more close. Feel more connected...it might help me calm down a bit in the environment"* [P17]. However, likely due to differences in **individual sensitivities to heat perception**, for P29 the temperature stimulation was overwhelming, especially when combined with vibration: *"That was kind of too warm for me. And I wasn't really comfortable with that. And then I had the vibrating thing here, so I was kind of like overwhelmed...it was too much then"* [P29].

Even in relation to "human" interpersonal warmth, eight participants indicated that they see heat as a sign of a crowded room, rather than individual body warmth: *"The welcoming and also like in the real environment, like if you go into a room where there's a lot of people that actually gives you more, like you can feel some heat from the people...so it feels more of a real environment"* [P17], unless it connects to the experience of touch: *"You should combine it with touch probably, to make the clear link"* [P23]. The ambiance of a signal also raised concerns about potential unnoticed "subconscious" effects such technology might have on users: *"I like the warmth of the device, but I dislike the fact that, for example, if I was using this product or something that it could subconsciously influence me as a person"* [P8]. While the trend was to find vibration uncomfortable or annoying, and warmth/heat unnoticeable or nice, this was not the same for all participants. Thirteen participants noted finding warmth *"really soothing"* [P22] or *fine, very clear, but not too hot or anything"* [P18]. Also, four mentioned being overstimulated and uncomfortable with heat. For ten participants, the combination of the haptic stimuli improved their overall experience: *"...I had the feeling when the vibration was going I was less annoyed by the vibration. Maybe that was because the heat was on, but it was much more subconscious. It was easier to rule out the vibration of the controller, it balanced it or something"* [P8].

4.2.4 Biosignals as humanness in an artificial agent. Biosignals such as heartbeat and warmth can be associated with the notion of humanness, with eight participants mentioning this drew them closer to the agent: *"I might probably go closer, I think, just based on how I feel. I think together (the heartbeat and body heat) they may create a sense of more human aspect to the agent"* [P14]. Fifteen participants noted that the **virtual experience does not have to replicate reality**, and instead offers a new affordance: *"It's actually interesting that it didn't spark as much of a reaction as I might have expected rationally. It felt quite natural that when I approached someone else I have this vibration and my assumption is that it needs to represent the heartbeat of that other person"* [P3]. Further, the fact that virtual agents are generating biosignals can contrast with the perception that virtual agents are likened to chatbots, robots, or even abstract entities: *Probably...yeah. But then, it would clash with the visual experience of the view, the artificialness...do you need them to be human, the avatars* [agents]*? Or could they be something else...like some abstract figure. You could exaggerate it in the other direction and then probably it'd be easier to connect with* [P23]. Three participants noted that the added layer of humanness on top of a virtual entity could create a somewhat uncanny feeling, touching on the controversial topic of **anthropomorphizing virtual agents with biosignals**: *"It does feel a bit creepy for me somehow in VR. Because it's very artificial and the heartbeat is something that is so close to the human experience and the life of people. So, like making it a link that is so direct is somehow disturbing. So, I don't know if it could connect me to the other people more. Maybe I would have to experience it a bit more thorough, but like maybe it will be strange"* [P23]. Not only the heartbeat, but the body warmth could also be perceived as a signal of life: *"The warmth that you go closer and then you feel that there is someone"* [P20].

4.2.5 Agency over accessing and perceiving virtual agent biosignals. Participants had conflicting views on receiving (but also sharing) heartbeats with virtual agents. P22 would prefer to feel people's actual heartbeats: *"I think it would be more comfortable for me if the other avatar* [agent] *was an actual person, then it would make sense. But if it's an avatar then I'm not so sure if I would want that information* [P22]; *Because usually you have the heartbeat that comes when you're really close to someone. So that feels like something that's a little bit private and it's also very revealing if you reveal your heartbeat to someone else...I think I'm happy that we don't feel that about persons"* [P20]. Others had to get used to virtual agents: *"As I kept getting closer and closer* [to the agent]*, I felt like the vibration became more pronounced for some reason and then to me that was like a stop. Almost like a negative, not to proceed further or get closer"* [P14]. Others felt self-conscious about how they may affect others' emotions: *"Maybe I would feel more uncomfortable knowing* [others' heart beat] *. Because maybe they thought that I was somehow influencing someone's feelings"* [P12]. This aspect of **uncontrolled emotion contagion** may require further **agency over biosignal access** – indeed, fifteen participants expressed that they would like to have more control not only of when their heartbeat might be shared, but also when they might listen on others' heartbeats: *"Perhaps I could only feel the heartbeat if I touch the person for example. Like if I put my laser on it"* [P2].

4.2.6 Getting into the body or out of the experience. The haptic stimulation had an intriguing divergent effect on participants' **(dis-)embodiment in the experience**. Eighteen participants recognized how haptic biosignals can add another "dimension" to the virtual experience, with potential for deeper engagement with their bodily selves in VR. However, it could equally have the opposite effect by being pulled "out" of their experience when drawing their attention to their real body outside VR: *"I think it does work really well with becoming aware of your own body, especially with the vibration and the warmth as well is I feel more aware, not necessarily of the space, but of my body itself outside of the VR world"* [P10]. This offers an opportunity where haptics could help participants become **more aware of their bodily feelings** and involved in the simulation: *"I could really see it working with like horror games and stuff, because you become aware of your own body within a virtual world. You can really feel like your life is on the line...it becomes a way more immersive experience I think"* [P10]. While this could potentially help gauge how participants are reacting to the agents' story or in adjusting IPD, for others who did not feel any haptic stimulation, it was easier for them to immerse themselves in the experience: *"Because of the physical, the vibrations and the warmth, I was more aware of there being a thing on me. And thus, I was less in the environment and more in real life"* [P9]. However, the longer participants stayed in the virtual environment, this **bifurcated sense of embodiment dissipated over time**: *"On the next trial...it was like getting more natural for me, like I didn't find it like, why my hand is vibrating. It was kind of more integrated with the situation"* [P29].

4.2.7 Giving space and needing space. Interview responses revealed how the interrelation between haptics and proxemics could be an effective **tool for setting personal boundaries**: *"If I'm very close and it's vibrating a lot I found it rather, not uncomfortable as such, but negative feedback to me. My interpretation was how much do you want me to approach them? It was kind of like a personal boundary. Like if it's vibrating a lot, I'm invading the personal boundary"* [P24]. The discomfort from such proxemic vibration led eighteen participants to take a step back and out of a barrier: *"Well, I wouldn't personally like the vibrations. Except if you want to create a barrier then that could be interesting"* [P5]. Eleven of these participants perceived haptics as a communicative act of the agent telling them to back off and give them space: *And if you felt that* [biosignals]*, then I think I would keep that normal distance again. That you unconsciously feel like 'hey, that's too close because I shouldn't feel this' "* [P18]. However, five of them were curious and purposefully tried to push these haptic boundaries: *"So I noticed that I was purposely getting a bit closer for it to get warm and then drew myself back again to get the sensation. I would say especially getting like super up close, like comically close, where I can't even see their face. That's the point where I was also getting warm and it kind of deterred me from it"* [P3]. People thus may feel like they need to be uncomfortably close, or are in fact uncomfortably close, to feel the virtual agent's heartbeat or body heat prominently.

5 Discussion

What is "virtually real" is increasingly enmeshed with "physically real" in which *social* reality is augmented. This brings new conundrums to age-old problems like immersion, presence, and embodiment with and through VR [9]. As we share our virtual worlds with artificial others, how people want to interact with, and become close, to virtual humans, becomes paramount to explore. Hence, we looked into how multimodal interaction in VR integrating thermal and vibrotactile stimuli influences the changing dynamics of human proximity to virtual humans.

Our qualitative results demonstrate that haptic biosignals are still ambiguous and unfamiliar to people. This was both in terms of how such cues are represented, as well as how people feel about haptic and thermal signals representing proximity to virtual humans. These aspects shed light on how quantitative results varied in how objective (actual distance) vs. subjective (felt distance) proxemics differed for multimodal cues, i.e., thermally-actuated body temperature (decreased objective but not subjective IPD) though vibrotactile heartbeats increased both subjective and objective IPD even if arousal and discomfort increased. To elaborate, we provide our discussion below.

5.1 How should virtual agents exhibit physiological properties?

An overarching goal of this work was to explore artificial haptic biosignals on virtual agents and their effect on user experience and digital proxemics in a social VR setting. To realize this, we drew on advances in haptic technology, wearable technology considerations, VR environment and agent modelling, and proxemics theory, to design two agent haptic biosignals (vibrotactile heartbeats and thermally-actuated body heat) that have the capacity to alter our affective interactions with virtual agents **(RQ1)**. Our work echoes prior findings that biosignals, when perceived visually [37, 59], can lead to inherent ambiguities (Sec. 4.2.1) in interpretation. Several factors lead to this, including ensuring clear signal-action coupling, a unified multi-sensory integration between the behavior of the agent and the felt signals, or more intelligent coupling between haptic actuations across modalities (whether visual, auditory, or somatosensory). For some participants, such ambiguities lead to the question of what the biosignals signify: is it a change within the virtual agent, or in the virtual environments? This parallels previous work by Lee et al. [59] who also find that avatars' visual indicators of heart rate and breathing were also sometimes attributed to the valence of a space. Indeed, recent work by Kocur et al. [53] has shown that visually manipulating properties of an avatar and the environment can modify thermal perceptions of cold and warmth and accompanying skin temperature.

We find that this leads to design opportunities when representing biosignals: either in a photorealistic manner by, for example, creating realistic blood flow animations on avatars/agents [67], or in an abstract form going beyond reality replication, for example by exploring new forms of bodily experiences triggered by emergent tactility and abstract embodiment representations in VR (cf., Embodied Telepresent Connection [17]). Further, whereas prior work found that biosignal visual animations can be a means to verify humanness in human avatars [59], here we found (cf., Sec. 4.2.4) that haptic biosignals added a layer of humanness to virtual agents – which could lead to increased anthropomorphism of AI agents. While more recent work has shown that more anthropomorphic agents can lead to increased trust in cooperative settings [56], earlier work by Nowak et al. [77] showed that participants reported less co-presence and social presence when shown highly anthropomorphic images, suggesting high expectations of the agent. More recently, Kim & Im [49] found that users perceive more humanness in highly intelligent but disembodied agents rather than in highly intelligent agents that have poorly designed appearances. While our work primarily dealt with IPD and comfort, the foregoing hints at what may come as an unintended side effect related to trusting artificially intelligent agents in the metaverse. The sense of 'humanness' that biosignals can imbue an agent with would affect our perception of these agents likely in either a compelling or an uncanny way. While haptically actuated biosignals, such as other's heartbeat are not mirroring our everyday experience of social interaction, they provide a novel opportunity for expressiveness of their presupposed internal states by artificial agents. By equipping virtual agents with biosignals, especially haptic representations that add an element of visceralness to users' experiences, it creates a knowledge gap of what would happen should virtual agents start (artificially) exhibiting haptically-actuated physiological reactions — what degree of uncanniness [73] would they transmit, and how would this influence our trust in them?

5.2 Haptic biosignals impact proxemics, user experience, and embodiment

We investigated the effects of virtual agent haptic biosignals on proxemic behavior and user experience **(RQ2)**. With respect to the effects of haptic biosignals on IPD, we found that warm temperatures decreased objective IPD but not subjective IPD to a virtual agent, whereas vibrotactile heartbeats increased both. Moreover, all participants largely remained in the social zone (Fig. 5), regardless of haptic feedback. With respect to temperature, our findings suggest a weak link between physical and interpersonal warmth (cf., [3]), paralleling replications [12, 108, 109] of studies that tested thermal displays in collocated and remotely located interactant settings. Considering both objective and subjective IPD, we find that thermal feedback did not promote proximity to a virtual agent, even when considering participants' subjective responses of potentially being drawn closer toward more human-like agents (cf., Sec 4.2.4). For vibrotactile heartbeats, we found that it not only increased IPD, but also resulted in greater perceived arousal and lower comfort than with thermal or no haptic feedback, which was echoed throughout our interview responses (cf., 4.2.3). However, we found (Sec. 4.2.7) that this gave rise to a particular use case: a tool for personal boundary setting. Indeed, designing for appropriate IPD in virtual settings is crucial when examining distance regulation within trait psychopathy [106] and harmful social behaviors in gaming contexts with NPC's [16], and more recently, understanding how marginalized groups experience harassment in social VR contexts [25]. To this end, vibrotactile heartbeats can function as a mechanism to ensure personal boundaries are trained and respected, even if dealing with virtual agents rather than fellow human avatars. Furthermore, we found no significant effects of agents' stories on subjective IPD, arousal, nor comfort. However, we find that the content of the agent monologue can be influenced by the haptic feedback (cf., Sec. 4.2.2), which aligns with prior findings by El Ali et al. [21] on how thermal feedback can influence the valence of neutrally-spoken voice messages. Interestingly, we found that when participants were engaged during the interaction with the agent, the haptic signals could be overridden. This supports earlier findings by Ooms et al. [78], who similarly found a haptic overriding effect when participants were engaged with videos, and found it may come with an unintended experience of a dark affective haptics [78] pattern, much like in our study P8 describing the potential subconscious effects. These dark design patterns can exploit our sense of touch through haptic technologies (e.g., smartphone vibrations) to make us do things we do not want to do. Within our context, this raises caution to when and how much should haptic actuation be used during virtual interactions. Lastly, while we found no significant differences in IPQ presence ratings across haptic feedback conditions, a key point mentioned by participants is how the haptic actuations affected participants' (dis-)embodiment in the experience (Sec. 4.2.6). This leads to a trade-off, by becoming more aware of one's bodily state, one can more easily get pulled out of the VR's place, plausibility, and embodiment illusion [94]. However, such effects could also dissipate over time, where the longer users spend time in rich haptic VR experiences, the more accustomed they become to such technology.

5.3 Ethical considerations and application areas

This research brings up several ethical considerations. One concern discussed in the above section is the risk of creating deceptive haptic patterns that could adversely influence human behavior subliminally. Additionally, when we augment virtual agents with a representation of biodata, we step into the territory of imbuing these agents with life-like characteristics which may have consequences for how we perceive and treat virtual agents. We could begin to anthropomorphize these agents, crossing the uncanny valley [96], shaping our feelings towards these computer-generated characters. Moreover, blurring of the lines between avatars (representing other humans) and virtual agents could in turn alter how we interact with other human users in virtual spaces. If we can no longer distinguish a real human from a virtual agent within a virtual interaction, some users may start treating human avatars in less respectful ways. Another ethical concern relates to who has control over the actuation. Since the actuation responds to proximity, in our setup the user controls the level of actuation by coming closer and further away from the virtual agent. However, in a different scenario if these haptic biosignals are implemented between two users, both of them have control over the distance between them, and thus one user trying to get closer could cause a physically uncomfortable experience for the other if they do not align on the desired closeness and level of actuation. Furthermore, different users may have different sensitivity to temperature and vibration actuation creating a possibility for unintended discomfort or even a risk of physical harm. Hence, a thoughtful design of the interface, prioritizing transparency of the technology and user control of their own experience, would be required to mitigate these concerns.

Taking these ethical considerations into account, we see potential application areas for both human-human and human-agent interaction in VR. Regarding human-human interaction, the main application area highlighted in our study is the communication of personal boundaries. As people might have a different sense of comfortable proxemics, this could lead to people unknowingly overstepping other people's boundaries. Participants highlighted vibrotactile heartrate could provide a signal to communicate this personal boundary, with a more intense signal communicating increased proxemic discomfort. This would generally improve immersants' comfort in interpersonal interactions and could particularly address harassment in extreme cases. Possible scenarios for such interpersonal interactions include virtual meeting/event spaces, social gaming environments, and professional training (e.g. cultural awareness training for international business as different cultures have different norms [104]). With human-agent interaction, the application area we see the most potential in is enriching communication channels for a more embodied interaction through augmenting verbal communication. With body warmth radiating around the agent, it could provide the feeling of the agent really being a someone who is there, as described by P20 in our study. Combining this with heart rate enhances the feeling of there being a 'human aspect' to the agent, making it more natural to approach the agent, as described by P3 and P14 in our study. Possible scenarios for such human-agent interactions include virtual meeting/event spaces (e.g. where agents facilitate an event) and virtual customer service settings where the agent should be approachable for client questions.

5.4 Limitations and future work

First, we have investigated two biosignals, within two particular haptic representations, and with respect to two gendered virtual agent designs, with scripted valenced monologues – we acknowledge that there may be myriad more factors at play that govern proxemic behavior in general (whether age [40], gender[15] [38], or emotional facial expressions [86]), and haptic proxemics in particular (cf., [2]). Nevertheless, we believe our work takes a necessary first step towards unpacking this new space of haptic biosignal proxemics. Second, given our study's focus on exploring haptic biosignals in a controlled setting, we restricted ourselves to simulated biosignal feedback, where we do not consider live biosensing nor more complex heartbeat parameters [68] and skin temperature fluctuations [39]. While our scope was to firstly represent heartbeats and skin/body temperature using vibrotactile and thermal displays and study their proxemic effects in VR, providing agents with real-time sensed biosignals can be a follow-up to this work. Similarly, while we assessed through self-reports participants' arousal and comfort levels with respect to haptic feedback, it would lend additional credence to further explore physiological measures (e.g, heart rate / HRV, skin conductance, and skin temperature in VR [28]). Fourth, based on our interview responses on the quality of stimulation (Sec. 4.2.3), we found that some participants hardly felt the heat changes, whereas others found the thermal actuation too hot. Thus, we may need to consider personalized calibration of thermal stimulation due to variations across human body temperature sensitivities [27], which may result in different proxemic zone temperature setpoints. Fifth, the interview responses also revealed that constant vibration can create discomfort or be overridden when captivated by another aspect of the experience, such as the story of the agent (Sec 4.2.2). Thus, we may need to consider alternative designs for future work such as action-coupled vibrotactile stimulation, for example when directing the laser at an agent, or vibrotactile heart rates as a warning cue when approaching the agent too closely. Sixth, some participants (Sec 4.2.5) mentioned that their interaction dynamics may differ had they interacted with human avatars, which warrants further analysis with respect to kept IPD for haptic biosignal proxemics. Seventh, we focused on single human-agent interaction, however, social VR spaces typically include a multitude of agents and avatars within the same environment (cf., [110]) – this raises the question of how such haptic biosignals could scale, without resulting in sensory overload and jeopardizing over user experience. Finally, it is worth exploring how other proxemic study approaches, such as the stop-distance paradigm [33], would influence haptic proxemic behaviors, especially to more carefully examine personal boundary settings in VR using haptics.

[15] While gender was beyond the scope and relevance of this work, we did statistically analyze participant and agent gender effects, however did not find any significant effects.

6 Conclusion

This work introduced the concept of haptic biosignal proxemics, focusing on two haptic biosignals of a virtual agent: vibrotactile artificial heartbeat, and thermally-actuated body temperature. Specifically, we explored the effects of haptic feedback and virtual agent valenced stories on proxemic behavior and user experiences in a VR human-agent interaction scenario. Our key findings showed (a) participants remained largely in the social zone regardless of haptic biosignals; however, while warm temperatures decreased objective IPD but not subjective IPD to a virtual agent, vibrotactile heartbeats increased both (b) vibrotactile heartbeats resulted in greater perceived arousal and lower comfort than with thermal or no haptic feedback (c) there were no differences in IPQ presence ratings across haptic feedback conditions (d) the importance of multi-sensory integration and action-coupling, the inherent ambiguity of haptic biosignals, how biosignals may imbue (uncanny) anthropomorphic features onto virtual agents, and how felt haptic experiences interplay with (dis-)embodiment in the VR experience. Our work distills design considerations for haptic biosignal proxemics and provides insights and cautionary considerations toward a future in HCI where we may 'feel' more from virtual agents using haptics during (social) VR experiences.

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