Influence of Haptic Feedback on Perception of Threat and Peripersonal Space in Social VR

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Fig. 1. Users immersed in a virtual dark alley watch a virtual agent slowly approaching them. The teaser image was lightened to enhance visibility. The agent can visibly emote anger or appear neutral, and as he advances, a belt wraps around the users' torso, simulating the users' shrinking peripersonal space. When feeling uncomfortable or threatened, users can choose to stop the progression of the agent by pressing a button. Results show that the body language of the agent and haptic stimulation of the observer both significantly influence users' perception of threat and their peripersonal space.

Abstract— Humans experience social interactions partly through nonverbal communication, including proxemic behaviors and haptic sensations. Body language, facial expressions, personal spaces, and social touch are multiple factors influencing how a stranger's approach is experienced. Furthermore, the rise of virtual social platforms raises concerns about virtual harassment and the perception of personal space in VR: harassment is felt much more strongly in virtual spaces, and the psychological effects can be just as severe. While most virtual platforms have a 'personal bubble' feature that keeps strangers at a distance, it does not seem to suffice: personal space violations seem influenced by more than simply distance. With this paper, we aim to further clarify the variability of personal spaces. We focus on haptic stimulation, elaborating our hypotheses on the relationship between social touch and the perception of personal spaces. Users wore a haptic compression belt and were immersed in a virtual dark alley. Virtual agents approached them while exhibiting either neutral or threatening body language. In half of all trials, as the agent advanced, the compression belt tightened around the users' torsos with three different pressures. Participants could press a response button when uncomfortable with the agent's proximity. Peripersonal space violations occurred 31% earlier on average when the agent was visibly angry and the compression belt activated. A greater tightening pressure also slightly increased the personal sphere radius by up to 13%. Overall, our results are consistent with previous works on peripersonal spaces. They help further define our relationship to personal space boundaries and encourage using haptic devices during simulated social interactions in VR.

Index Terms—Affective haptics, Social VR, Threat perception, Peripersonal space, Social agents

1 Introduction

As virtual spaces develop, so do the ways in which users can interact. Since 2014, with the launch of VRChat[1], VR social media platform have risen in popularity. More recently, Meta opened their game Horizon Worlds[2] to the public in 2021. Sharing a virtual space can be very different from a physical one, as virtual avatars do not need to be humanoid, and there are no real surface boundaries. Common social norms, however, do not seem to change much in appearance [25]. While interacting with others or with virtual agents, users adhere to similar social spatial behavior, e.g. maintaining culturally appropriate interpersonal distances [27] and generally looking other in the eyes when speaking to them [25]. Studies have shown that the behavior and overall appearance of a virtual avatar impacts users' social perception of them [22, 40]. Correlated with physical distance, social

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[1] https://hello.vrchat.com

[2] https://horizon.meta.com

touch is also a significant factor in the perception of a social interaction [3, 35]: when reducing physical distances, there comes a point where users can touch each other, in greeting or to convey emotions. Since virtual spaces can intensify experiences, this can also impact the perception of a negative interaction. The sum of all these factors underlines the variability of users' personal boundaries: context, perceived agency, and tactile feedback can add a significant dimension to social interactions.

Virtual personal space boundaries, or peripersonal spaces (PPS), seem coherent with the physical world [27]. The appearance and behavior of virtual avatars [46] does impact the interpersonal distances that users want to keep, in accordance with their PPS: an angry or drunk-looking agent will encourage users to stay further away. This avoidance behavior is similar for pedestrians when confronted with perceived danger in public spaces [8, 31]. While virtual environments are generally successful at creating the experience of existing places, VR also allows us to control user perception to a greater extent than in the physical world. For example, optical illusions can modify the perception of a virtual space [41], and haptic devices can provide tactile stimuli to accompany or enhance events. One such example is the use of social haptics in VR [34]. Taking into account these factors, it stands to reason that the addition of haptic stimuli would impact the perception of PPS boundaries.

Unfortunately, virtual social interactions sometimes include acts of online harassment [49]. Since 2014, multiple cases of cyberbullying, sexual misconduct and even sexual assault have been brought to light [44, 54]. In 2016, one victim described being forcefully groped in front of her family, while trying to play a cooperative archery game in VR: "I hadn't lasted three minutes in multi-player without getting virtually groped [...] it felt real, violating" [6]. This event added fuel to a preexisting debate [17] on the gravity of sexual harassment in VR [56]. When Meta launched their platform in 2021, it was revealed that "VR groping" was still an issue, as reported by their beta testers [5]. More recently, a young girl from the UK was virtually sexually assaulted by a group of adult men while using Meta's Horizon Worlds [12]. While the victim was not physically harmed, as everything happened virtually, police officers reported she suffered emotional and psychological trauma akin to a 'physical' rape victim. Since virtual immersive spaces are designed to trick and enhance users' feelings of embodiment and presence, it stands to reason that traumatic events would yield similar psychological responses. Meta's beta tester who reported having been virtually groped supported this view: "Being in VR adds another layer that makes the event more intense. Not only was I groped last night, but there were other people there who supported this behavior which made me feel isolated" [5].

According to Meta, while the events themselves are tragic, the platform does include a protective feature against strangers and harassers that victims could have used [5]. Their "Safe Zone" is a protective bubble users can activate to prevent others from touching, talking, or interacting with them in any way. The rings around users force a distance of 4 feet or 1.2 meters between them, which should suffice in protecting users. Unfortunately, the numerous reported cases of virtual harassment only serve to emphasize the ineffectiveness of this feature [5]. While the intention behind the feature seems sound, its nature relies on users' knowledge of the feature and their ability to react and protect themselves when perceiving a threat.

In this paper, we investigate the variability of our peripersonal spaces. Previous works have illustrated the impact of tactile feedback on social interactions [19, 35], and we know that it can influence the perception of PPS [3, 29]. Against this background, we asked whether the addition of haptic stimulation to a social interaction influences the perceived size of users' PPS. We measured user responses to encounters with a virtual agent in a dark alley. Users sat in a physical chair, wearing a haptic device around their torso. The device included a servomotor that could tighten an elastic belt around the stomach. When users entered the virtual alley, the agent would start approaching them. The agent's body language expressed either anger or was neutral, and the haptic belt could be turned on or off. The relative applied pressure of the belt varied between 3 values: P_0, $P_1 = P_0 * 140\%$, and $P_2 = P_0 * 180\%$. A response button allowed users to indicate when they felt uncomfortable with the agent's distance and in 50% of cases, pressing the button caused the agent to stop approaching. The agent continuously approached users for 6.5 s until either the users stopped him or he crossed the threshold distance of 5 cm to the users, at which point he disappeared and the haptic belt was unwrapped. This trial was repeated a total of 240 times, with variations in the agent emotion, belt activation, and applied pressure of the belt. For each trial, we recorded the distance at which the agent was requested to stop, and after the experiment users answered questionnaires on their perception of the experience and of the haptic stimulation.
After reviewing the literature, we will develop and explain our methodology and the haptic and VR technology used. Section 4 will then summarize the observed data which will be analyzed and concluded upon in the following sections.

2 Related Works

2.1 Nonverbal social perception

2.1.1 Proxemics and personal distances

Proxemics is an integral part of nonverbal communication [24]. This field pertains to the human use of space and its influence on social interactions and behaviors; humans all have a space around them that they usually define as their 'personal space bubble'. This space can vary in size according to personal boundaries and usually stays in a sphere around the individual [28]. Interpersonal distances, or proxemic distances, can then be separated into four subcategories [24]. From closest to farthest to the body: intimate, personal, social, and public distances. Intimate distances are generally reserved for lovers and dance partners, personal for friends and family, social for acquaintances, and public for other interactions. A closely related concept in cognitive neuroscience is that of peripersonal space and it refers to the region surrounding one's individual body, which suggests greater behavioral relevance for stimuli and actions occurring within it [11, 15, 48, 50].

2.1.2 Kinesics and body language

Other aspects of nonverbal communication include kinesics - gestures, body language, and facial expressions - and haptics, communication by touch. Hans and Hans [26] categorized proxemics and proxemic distances as a subcategory of haptic communication. They argued that interpersonal distances are often metaphorically referred to by physical distances, whether they are emotional or truly physical. Bailenson et al. [4] studied the influence of social VR on proxemic behavior. They underlined the importance of avatar distance and behavior, and observed behavioral patterns consistent with previous works on face-to-face interactions. Hans and Hans [26] emphasized the importance of relationship levels for PPS. A stranger unexpectedly approaching too closely would breach social norms and appear aggressive. Aggressive facial expressions and postures such as visible anger would then intensify the negative perception of the stranger, pushing the individual to identify the stranger as a social threat. However, while behavior and body language influence social perception, haptic stimuli may be of equal importance when evaluating a social interaction. Virtual and physical avoidance behaviors are often studied in public spaces, by varying the appearance of the environment or the agent's behavior [8, 46]. Adding social touch as a variable might yield different results, like attenuating the effects of the agent's behavior, or enhancing them.

2.1.3 Social threats

Threat perception has been a subject of investigation in psychological and neuroscientific research for several decades [22, 39, 62]. With virtual reality (VR), much more naturalistic, ecologically-valid investigations of this complex process are possible [55]. Experiments have shown that the context in which the threat is perceived can have a significant effect on the threat response, when measured with skin conductance [33] and with electroencephalography (EEG) [57]. Mello et al. [42] looked specifically at social threats and found emotional body expressions and spatial proximity as important factors for social threat perception. Specifically, heart rate and postural mobility were reduced, signs of a ‘freezing’ behavior, in response to aggressive-appearing and proximal avatars. Concomitant with this was a finding of increased responses in several brain regions to socially threatening stimuli approaching a participant, especially when entering their peripersonal space [15]. Lu et al. [40] showed that not only the emotional expression of the avatar, but also an individual’s level of control over the threatening situation had an effect on threat perception, as indexed by both EEG signals and PPS perception.

2.2 Affective haptic feedback

2.2.1 Social touch

Haptic devices are defined by their ability to transmit information and enhance the user’s environment [14]. This is especially useful in VR, where sensory stimuli can otherwise be found lacking. Haptic stimulation can therein enrich and enhance user perception of virtual environments [14]. A specific field in haptics research is the study of affective feedback, where haptic devices are designed to convey emotional states and feelings. One of the most common types of affective haptics is mediated social touch, i.e., using hugs or caresses as a means to convey affection and relaxation during human-human interactions [34, 59]. Conveying such positive emotions or helping users relax [47] is a popular application of haptic technology. In this paper, we chose to focus on influencing the social perception of humanoid virtual agents and the subsequent user’s peripersonal space in a user-agent interaction.

2.2.2 Fostering trust and friendliness

Saint-Aubert et al. [52] used vibrotactile stimuli to augment verbal interactions between users and virtual agents. In a virtual room, users listened to the dialogue of two agents debating. One agent’s speech was supported by synchronized vibrotactile stimuli, directly adapted from the speech’s audio file. Users reported they felt the ‘supported’ agent was more charismatic and convincing. The vibrotactile feedback also heightened their perception of the agent’s virtual presence. The experiment was replicated and developed upon by Hecquard et al. [30], who found similar effects of warm thermal stimulation on the perceived friendliness and persuasion of virtual agents. Huisman et al. [34] and Valori et al. [60] highlighted the importance of affective touch during social interactions. Valori et al. found a reciprocal link between using social touch and the perceived trustworthiness of an interlocutor. This perception of trust influenced user behaviors and was in turn influenced by an increase or decrease in social touch.

2.2.3 Affecting the perception of peripersonal spaces

Hecquard et al. [29] used a compression belt and vibrotactile feedback to convey feelings of anxiety and sadness based on common physiological responses to stress. The study aimed to transmit the stress of a virtual agent experiencing technical and social difficulties during a professional presentation. Users reported higher feelings of anxiety, empathy, and social connection when experiencing the physiologically-based stimuli.

Fay et al. [20] studied the influence of physical temperature on the perception of spatial proximity. They found users generally perceived warm objects as physically closer, and cold objects as further away than the actual distance. This follows several previous works by Fay and Maner [19] and IJzerman et al. [35] on social warmth, linking physical temperature to social affiliations.

Andersen et al. [3] reviewed the importance of proxemic and haptic behavior during influencing or full-on intimidation attempts. The authors underlined the power of social touches and physical distances, highlighting their impact during acts of intimidation and harassment. They noted the universality of human proxemic and haptic behavior, while acknowledging cultural and individual differences in PPS and acceptable social touches. Overall, the link between social touch and the perception of PPS is indubitable. Universally, common social rituals include hugs, kisses, and other tactile interactions among close friends or family. Conversely, the authors highlighted the impact of proximity and tactile stimuli during social interactions. When in a positive context, the stimuli can enhance persuasion and feelings of familiarity [30]. The existing literature justifies the subsequent study of haptic stimuli to influence PPS boundaries in virtual environments.

3 Method

3.1 Participants

40 healthy participants with normal or corrected-to-normal vision were recruited for the study. All participants were completing a university degree fully taught and assessed in English. Participants attended a single one-hour experimental session. They provided written consent at the start of the experimental session and earned participation credits or money as remuneration. The data of 30 participants (5 males, 24 females, and 1 non-binary/third-gender person; mean age = 22 ± 2.9 years) were included in the analysis. Most users (57%) had never interacted with haptic devices before; 33% had tried it before, and 10% had regular contact with it. As for VR, 30% had never tried it, 40% had tried it once, and 30% had regular contact with it. Of the 40 participants, 4 were excluded from the analysis due to issues with the experimental setup during data collection. Additionally, 6 participants were excluded for responding on fewer than 12% of all trials. Under this threshold, the behavioral analysis was rendered useless by the lack of variability in the data. We also verified that the general conclusions did not differ much with or without the 6 participants. The rest of the participants responded around 93% of the time, with a median and a standard deviation of $Mdn = 99.6\%$, $SD = 14.3\%$. Users reported no symptom of fatigue. The study was approved by our local Ethics Review Committee on Psychology and Neuroscience.

3.2 Apparatus

We used a wearable haptic system able to dynamically create a physical sensation of pressure to users during the approach of a virtual agent.

3.2.1 Haptic device - Compression belt

The compression belt is inspired by the device presented by Moullec et al. [43]. It is composed of a strap-based, 3D-printed plate that users can wear and easily adjust to their own torso. An elastic belt is fastened around the user’s waist, actuated by a servo motor to control the belt length so as to apply pressure dynamically. Figure 2 shows a user wearing the device, with a close up of each moving component. This design slightly differs from the previous ones, as the 3D-printed back is much lighter than the large wooden plaque, and its smaller size and straps allow for easier wear and adjustment.

The pressure of the tightening and loosening activity of the belt simulated the approach of the virtual agent, e.g., the stronger the belt tightens, the closer the agent is; the faster the belt tightens, the faster the agent seems. The relative applied pressure of the belt varied between P_0, $P_1 = P_0 * 140\%$, and $P_2 = P_0 * 180\%$. These pressures were achieved with 3 wrapping speeds on the motor: 50, 70, and 90 rpm (rotations per minute). For each scene, when the agent started walking, the belt would start wrapping at whichever pressure was chosen. The unwrapping would only start when the agent stopped. At the beginning of the experiment, we carried out a belt calibration according to each user’s body morphology. The belt tightened slowly around the participant’s body until it rested comfortably on the user’s waist without causing pressure on the participant’s torso. This personalized calibrated position was the baseline at which the belt would begin tightening; at the end of each haptic trial, the belt would then loosen back to this baseline position.

3.2.2 Virtual environment

The experiment was designed using Unity3D. Participants wore a HTC Vive Pro VR headset to visualize the scene. Additional details about the content of the scene are reported in Section 3.3.1.

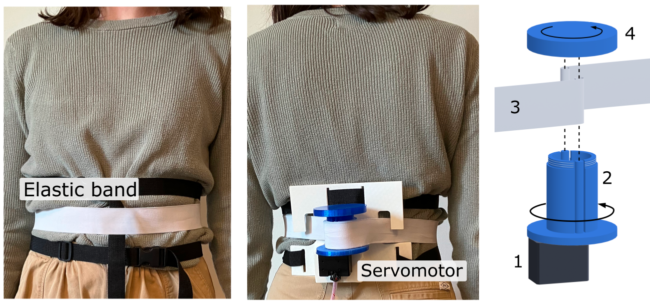

Fig. 2. Close up view of the haptic device. An elastic band (3) is attached to a cylinder (2) and wrapped around the user's torso. The cylinder rotates thanks to a servomotor (1), wrapping the band and tightening it around the user's torso. The actuator itself is attached to a 3D-printed plate made in pliable plastic. The plate is fastened to the user via two adjustable black bands above and below the cylinder. A lid (4) is screwed onto the cylinder to prevent the band from slipping out.

3.3 Experimental procedure

Prior to commencing the experiment, participants were first informed about the task design and procedure. They were then fitted with the compression belt. The participants sat down on a height-adjustable chair and put on the headset, which was mounted on a chin rest, allowing the participant to rest their head, thereby reducing fatigue from wearing the VR headset. The height of the chair was adjusted for each participant to maximize comfort.

In the first stage of the experiment, participants had the opportunity to familiarize themselves with the VR environment in an exploration phase. The participants were able to move their head to familiarize themselves with the 3D environment. Participants indicated when they felt sufficiently immersed and ready to proceed to the experimental task. After the exploration phase, the compression belt was calibrated to the participant, and the participants completed the experimental task.

3.3.1 Experimental task

The experimental task was adapted from a previous study [40]. The VR environment consisted of a dark, urban alley, where participants would be approached by a virtual agent walking towards them from one end of the alley. The agent wore neutral clothing and had a blurred face, so that participants focused on body language. The agent approached either in a threatening manner (raising arm and fist as if to punch the participant) or in a neutral manner. While their body language differed, their walking speed remained identical. Both agents are visible in Figure 1. Participants were instructed to press the response button as soon as they felt uncomfortable and wanted the agent to stop approaching, but were told that there was only a 50% chance that pressing the response button would stop the agent. The participants were aware that pressing the button would not guarantee an effect on the agent. This was done to ensure that participants did not have a sense of full control of the task and thus were more likely to feel threatened.

Participants completed 6 blocks of the experimental task and each block consisting of 40 trials adding up to a total of 240 trials per participant. The haptic belt tightened around the participant's waist on 50% of all trials. Each block featured a different wrapping pressure (P_0, P_1, or P_2). At the start of each trial, the agent appeared in the alley, 10 meters away from the participant. After 1.0 +/- 0.1 s of the agent being static, it began to approach the participant for 6.5 s at a speed of 1.54 m/s. On trials where the participant successfully stopped the approach of the agent by pressing the response button, the agent remained static until the beginning of the next trial. On trials where the participants did not or could not stop the agent's approach, the agent continued its approach until reaching the participant and the end of the trial. This was followed by an inter-trial interval of 5.0 +/- 0.1 s during which a fixation cross was presented in the center of a black screen and the belt could reset to the calibrated baseline position. This series of events is visualized in Figure 3.

The study used a 3x2x2 within-subject design with three belt pressures (P_0, P_1 and P_2), two agent emotions (angry, neutral), and two haptic conditions (haptic belt stimulation, no haptic belt stimulation). In trials with haptic feedback, the compression belt tightened in a stepwise manner over 6 steps as the agent approached the participant. The pressure of tightening was kept constant for a block of trials. In trials with no haptic feedback, the compression belt remained static in the calibration position for the duration of the trial. Each participant completed two experimental blocks of each belt tightening pressure. The order of the pressures was randomized for each participant. Within an experimental block, there were 10 trials of each possible combination of agent emotion and haptic feedback presence. The duration of the experimental sessions was 50 minutes (3 belt pressures x 2 agent emotions x 2 haptic feedback conditions x 20 trials per condition combination x (1.0 s static agent + 6.5 s approaching agent + 5.0 s inter-trial interval) = 3,000 s = 50 minutes).

3.4 Hypotheses

From previous research, we gathered that the sense of agency mattered to users when perceiving negative social cues from virtual agents [40]. Increased feelings of virtual presence and embodiment can heighten the impact of virtual scenarios on users [53, 55], and haptic feedback has been shown to intensify feelings of immersion in virtual spaces [34] as well as the social perception of virtual agents [32]. Building on these results, we developed three hypotheses on the expected outcome of our experiment.

- **H1**: The visual cues of the virtual agent's emotional state will affect users' peripersonal space boundaries.
- **H2**: Augmenting the agent's social cues with haptic feedback will affect users' peripersonal space boundaries.
- **H3**: Increasing the intensity and pressure of the haptic stimulation will heighten the impact of the haptic device.

3.5 Evaluation criteria and metrics

Participants answered two sets of questionnaires: mid- and post-experience. All questionnaires were written in English. As a behavioural measure, each trial recorded the distance of the agent to the user when he stopped. The **mid-experience** questionnaire happened after each experimental block. The participants had a short break, and rated the intensity of the belt feedback on a scale of 1 (least intense) to 10 (most intense). After the VR session was completed, each participant filled out a series of **post-experience** questionnaires. The first included simple demographic questions on age, biological sex, and technical experience with VR and haptic feedback. We assessed their cybersickness levels with the VR sickness questionnaire [37].

User experience of the belt was evaluated with 12 questions, including 9 7-point Likert scales ranging from 1 "When the belt was not moving" to 7 "When the belt added pressure":

- **Q1** - I felt more anxious/scared;
- **Q2** - I felt more relaxed/calm;
- **Q3** - I felt more present in the scene;
- **Q4** - I felt more disconnected from the scene;
- **Q5** - I felt more threatened/the agent looked more menacing;
- **Q6** - I felt safer;
- **Q7** - I felt my personal space was breached quicker;
- **Q8** - I found a link between the haptic feedback and the VR scenario;

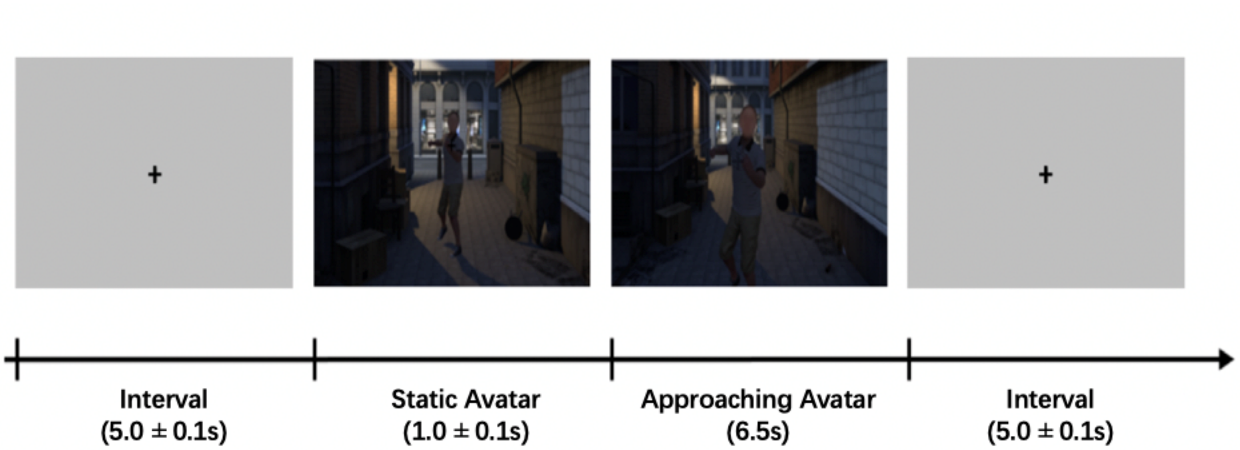

Fig. 3. An overview of the experimental trial. Each trial began with the appearance of the agent at first standing still for 1 second. The agent then approached for 6.5 seconds during which time the compression belt tightened on 50% of trials and participants had the opportunity to press the response to button to attempt to stop the agent's approach. The button press successfully stopped the agent on 50% of all trials. This was followed by an inter-trial interval of 5 seconds.

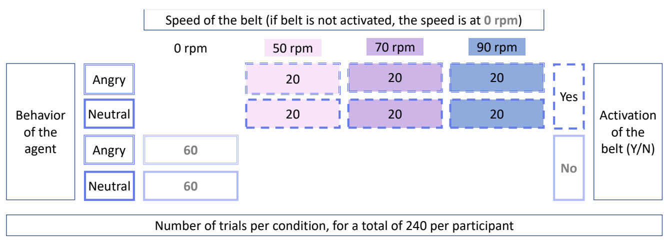

Fig. 4. Overview of the different experimental conditions. The 240 trials were divided into 2x2x3 groups of 20 each; according to the behavior of the agent (Angry/Neutral), the activation of the belt (Yes/No), and the speed of the belt if activated (50/70/90).

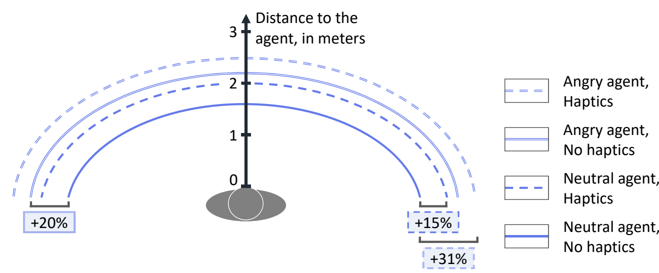

Fig. 5. Influence of the virtual agent's visible emotion (Angry vs. Neutral) and of the belt's activation (Haptics vs. No haptics) on users' perceived PPS. When the agent was angry and the belt was activated, the PPS size was increased by 31% on average: users felt the agent violated their PPS boundaries from farther away.

- **Q9** - I believe that the haptic feedback modified my perception of the VR scene.

Users answered 3 additional questions on their personal experience during the experiment.

- **Q10** - Did you perceive a difference between the two conditions (Haptic feedback vs. No-Haptic feedback)? (Y/N)
- **Q11** - In what percentage of trials did you feel a pressure sensation given by the belt? (0-100%)
- **Q12** - In which way did the conditions influence your strategy and behavior in reaction to the agent? (Explain)

4 Results

The normality assumption was verified using Shapiro-Wilk's test of normality. We analyzed the data using a Univariate Type III Repeated-Measures ANOVA. The sphericity was verified with Mauchly tests and corrected if needed with the Greenhouse-Geisser and Huynh-Feldt methods. For the non-parametric results, the Friedman rank sum test was used. If a significant effect was found, a post-hoc analysis via the Wilcoxon Rank-Sum test was performed to check the significance of the pairwise comparisons. The Holm-Bonferroni correction was applied to the p-values to account for multiple comparisons. We used Pearson's Chi-squared test to assess the influence of the different factors on the appearance of a user response. Means, medians, and standard deviations will respectively be mentioned as M , Mdn, and SD. Spearman's rank correlation assessed relationships between variables.

4.1 Behavioral measure: user response

For each trial, we recorded the distance between users and the virtual agent. When users tried to stop the advancing agent, whether they succeeded or not, their distance to the agent in meters was recorded. We refer to the distance as the meters the agent was from the user when they pressed the button; e.g. a distance of 2.5 m means the participant pressed the response button when the agent was 2.5 m away from them. Trials where users did not react and let the agent approach until the end were recorded as 'No reaction'; we included them in the following Figures 6-8 as a distance of 0 m for easier visualization. For easier comprehension of the differences between conditions, the distances were also translated into PPS size percentages: e.g., the perceived PPS of users, distance at which they thought the agent was too close for comfort, was augmented on average by 13% when the belt was activated compared to when it was not. This effect is visualized in Figure 5. The users' reported preexisting experience in VR and haptic devices did not significantly influence the results (respectively $\rho = -0.1$, $p = 0.447$ and $\rho = -0.9$, $p = 0.643$). We did not observe any order effect: the distance recorded in each trial did not significantly evolve with time ($\rho = -.01$, $p = 0.375$).

4.1.1 Emotion of the virtual agent

Users reacted significantly more often when the agent showed anger ($\chi^2(1) = 39.503$, $p = .0001$). Users reacted 95% of the time when the agent was angry, and 90% when he appeared neutral. The distance at which the agent was stopped was also influenced by the emotion shown

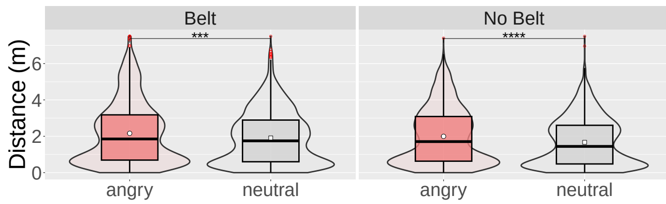

Fig. 6. Influence of the virtual agent's visible emotion (angry vs. neutral) on the agent's distance to the user when stopped, w.r.t. the belt's activation.

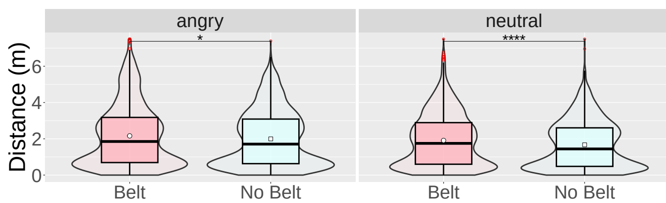

Fig. 7. Haptic belt's influence on the agent's distance to the user when stopped, w.r.t. the virtual agent's visible emotion (angry vs. neutral).

($F_{1,28} = 21.83,\ p = .0001$). The agent was stopped sooner by users when angry than when neutral ($p = .0001,\ r = .09$: respectively, in meters, $M = 2.1,\ SD = 1.6$ and $M = 1.8,\ SD = 1.4$). Translated into percentage, the users' PPS increased by 17% when the agent appeared angry, compared to the neutral agent. This effect is visualized in Figure 6.

4.1.2 Belt vs. No Belt

Users reacted significantly more often when the belt added pressure ($\chi^2(1) = 41.928,\ p = .0001$). Users reacted 95% of the time when the belt was active, and 90% when the belt was not. The activation of the haptic belt also significantly influenced the user response ($F_{1,28} = 4.99,\ p = .034$). Users stopped the agent's approach significantly sooner when the belt was adding pressure than when it was not moving ($p = .0001,\ r = .09$: respectively, in meters, $M = 2.0,\ SD = 1.6$ and $M = 1.8,\ SD = 1.4$). Translated into percentage, the users' PPS increased by 13% when the belt was activated, compared to when it was not. This influence is illustrated by Figure 7.

4.1.3 Applied pressure of the device

Users reacted slightly significantly differently depending on the relative pressure applied by the haptic belt ($\chi^2(2) = 10.374,\ p = .005$). With P_0, users reacted 96% of the time. They reacted 94% of the time with $P_1 = P_0 * 140\%$ and $P_2 = P_0 * 180\%$. As visible in Figure 8, an increase in the applied pressure of the belt had a slightly significant influence on the user response ($F_{2,58} = 3.44,\ p = .039$). When the agent showed visible anger, trials with either P_1 or P_2 had significantly higher distance measures than trials with P_0: for P_0, $M = 2.0,\ SD = 1.5$ m, for P_1 $M = 2.1,\ SD = 1.5$ m ($p = .044$ difference with P_0), and $M = 2.2,\ SD = 1.7$ m ($p = .021$ difference with P_0) for P_2. This means that users let the agent come closer when the applied pressure was lighter (P_0). Compared to the initial pressure (P_0), users' PPS increased respectively by 5% and 13% with the increased pressures of P_1 and P_2. When the virtual agent appeared neutral, this effect decreased slightly and only P_2 trials significantly differed from P_0 ones ($M = 1.9,\ SD = 1.6$ m vs. $M = 1.7,\ SD = 1.4$ m, $p = .031$, 9% increase in PPS with P_2).

4.1.4 Interactions between factors

We noticed interaction effects between the 3 factors (haptic activation, agent emotion, applied pressure) for their influence on user PPS. There was a slight interaction between the haptic feedback and the agent's visible emotion ($F_{1,28} = 3.19,\ p = .085$). While this effect was not significant, the subsequent Wilcoxon tests revealed significant differences between the conditions AngryxBelt and AngryxNo Belt, as well as

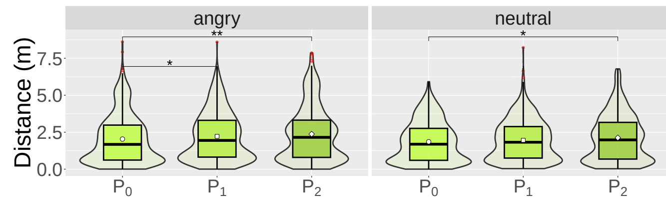

Fig. 8. Influence of the haptic belt's applied pressure on the agent's distance to the user when stopped, w.r.t. the virtual agent's visible emotion (angry vs. neutral).

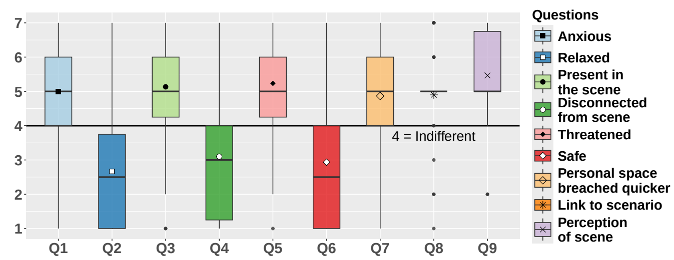

Fig. 9. User opinions on the haptic belt, questions **1-9** in order. 1 = the belt was not moving, 7 = the belt added pressure. For example, answering 5 for **Q1** would mean "I felt rather more anxious when the belt added pressure".

BeltxAngry and BeltxNeutral. An absence of haptic feedback heightened the influence of the angry agent ($p = .0001,\ r = 0.12$ vs. $p = .0005,\ r = .07$ with belt activated), while a neutral emoting from the agent heightened the influence of the haptic belt ($p = .0001,\ r = .09$ vs. $p = .027,\ r = .04$ with angry agent). These differences are visible in Figures 5, 6, and 7.

4.2 User perception of the haptic belt

4.2.1 Intensity ratings

The intensity rating of each block did not significantly differ between pressure levels ($\chi^2(2) = 2.54,\ p = 0.28$), but the order of the blocks did influence it ($F_{80.79,2.79} = 12.62,\ p = .0001$). A Wilcox pairwise test revealed that the intensity rating of the first block was consistently rated as significantly lower than the other blocks, regardless of applied pressure ($Mdn = 5,\ SD = 2.0$ for block 1 and on average, $p = .005,\ r = -0.36,\ Mdn = 6,\ SD = 1.9$ for the other blocks). The second block was also significantly lower rated, to a lesser degree ($Mdn = 6,\ SD = 1.8$ for block 2 and on average, $p = .05,\ r = -0.21,\ Mdn = 7,\ SD = 1.9$ for blocks 3 to 6).

4.2.2 Likert scales on the haptic belt

Answers to questions **1** to **9** on user experience of the belt are shown in Figure 9. Users stated having felt significantly more anxious and less relaxed when the belt was adding pressure (respectively, $p = .0003,\ r = 0.80$ and $p = .0006,\ r = -0.73$). Similarly, they felt more threatened and less safe with the belt active (respectively, $p = .0004,\ r = .75$ and $p = .005,\ r = -0.60$). Their perceived personal space was breached quicker ($p = .008,\ r = 0.57$) and their perception of the scene changed more ($p = .002,\ r = 0.62$). Users found a slightly higher link to the scenario when the belt was moving ($p = .0001,\ r = .83$). They felt more present in the scene and less disconnected from it with the belt (respectively, $p = .002,\ r = 0.64$ and $p = .008,\ r = -0.56$).

Out of 30, only one user reported not perceiving the difference between the two haptic conditions (**Q10**, Haptic vs. No haptic). Overall, users reported having perceived the belt move in over 50% of trials (**Q11**, $M = 59.17,\ SD = 20.21$).

4.2.3 Thematic analysis of participant feedback

The users' responses to **Q12** were analyzed using thematic analysis [10]. In responding to the question, they were free to express themselves and were not limited by time or word count. To then understand the underlying themes, the answers were carefully evaluated one by one. Then, themes regarding various parts of the experiment or difference in reaction were developed. The main overarching themes concern the users acting in response to the haptic stimulation, in response to the agent, or the participants identifying a more general approach without specifying a part of the experiment. A detailed summary of the themes can be found in Supplementary Table **??**. The larger themes regarding the haptic stimulation include an effect where the haptic stimulation increases the engagement in the scene, where it plays a neutral role, and where it reduced engagement. The most common theme was that of the belt leading to a quicker reaction, highlighted by 14 participants.

5 Discussion

We replicated the findings of Lu and colleagues [40] and showed that participants felt uncomfortable sooner and responded more often when presented with an approaching angry agent than an approaching neutral agent. Expanding on the previous study, we found that haptic stimulation also led to more efforts to maintain greater distances with the approaching agent. We observed a significant interaction effect between the agent's emotion and the presence of haptic stimulation, suggesting a greater effect of the haptic stimulation when the agent was neutral than when it was angry. The inclusion of the haptic stimulation also significantly affected participants' subjective experience of the scenario, leading to greater feelings of threat and anxiety and reduced feelings of relaxation and safety. We also found the different applied pressures of the haptic belt to have a significant effect, with greater pressures leading to feeling uncomfortable sooner. This effect of applied pressure on the participants' behavior was observed even though the participants themselves did not report any differences in their perception of the haptic stimulation when asked to assess the intensity of the belt tightening. We did observe a trend in which the participants always rated the intensity of the first block of trials they experienced as lower than that of the remaining blocks, regardless of the actual applied pressure during the bloc. Finally, an analysis of the users' own subjective perception of the entire study showed that while the majority had an experience in line with the statistical findings, some had an entirely opposite perception, namely finding the haptic stimulation to be comforting and/or distracting from the visual threat. We now discuss each of these findings in turn.

5.1 Threat perception and peripersonal space

Our finding that an approaching threatening agent compared to an approaching neutral agent leads to an earlier response of feeling uncomfortable and thus a larger peripersonal space replicates several previous findings on the effects of facial expression on PPS [13, 16, 40, 51]. As hypothesized, we also showed that haptic stimulation can have a similar effect on the PPS, with the tightening of the belt leading to an earlier response and thus a larger radius of the PPS. To our knowledge, this is the first demonstration of haptic stimulation affecting peripersonal space, and one of a few showing the conveying of negative interpersonal emotions via haptic devices. There have been studies in the past, which have successfully conveyed positive interpersonal emotions via haptic stimulation [36, 59, 61] and we present evidence for the broadening of the possibilities of haptic devices.

Notably, we found a significant interaction between the emotion of the agent and the presence of haptic stimulation. The tightening of the belt had a greater effect on the radius of the PPS when the agent was neutral than when it had an angry expression. We propose that this pattern of responses can best be explained with a Bayesian model of multimodal cue integration [2, 18]. When presented with the experimental scenario the participant must assess the available information and make a decision about when to act, pressing a button, which has a chance of stopping a potentially threatening agent from approaching. At any given moment, the participant must decide if the perceptual input suggests threat and whether to press the button. The visual information of an approaching angry agent is highly salient and leaves little doubt for the user about the threatening nature of the scenario. While the concurrent haptic stimulation may reinforce this impression, it does not significantly affect the participant's impression of the scene. However, when the approaching agent has a neutral body expression, the potentially threatening nature of the event is less clear and so the participant must rely more on the haptic information provided. In more Bayesian terms, with the neutral agent, the visual input has a lower weighting in the decision about the presence of threat, leading to a greater contribution of the haptic input than when the agent has a threatening body expression. This Bayesian integration of multimodal cues could be well integrated into Bufacchi and Iannetti's action field theory of peripersonal space [11], affecting the gradation of the multiple PPS fields they propose.

5.2 Immersion and subjective perception

The results of the questionnaire completed at the end of the experiment showed that the addition of the haptic stimulation made the participants feel more anxious, threatened and present in the scene, less relaxed, safe, and disconnected, as if their personal space was breached faster, and the belt affected their perception of the scene. This overwhelmingly shows that the inclusion of the haptic stimulation significantly affected participant's subjective experience of the entire experiment, significantly increasing their immersion. This is in line with previous studies, which have used haptic devices to increase immersion in a virtual environment [1, 7, 21, 45].

The participants also had an opportunity to describe their experience of the task with a particular focus on the haptic stimulation. Thematic analysis of the responses revealed two contrasting impressions of the belt. While the majority of the users found the belt tightening to increase their anxiety and lead them to respond sooner, some instead found the belt to be reassuring / distracting them from the approach of the agent. The haptic stimulation provided by the tightening of the belt is somewhat akin to that provided by the HaptiHug [59], also a belt around a participant's waist, which in combination with shoulder straps and rubber hands simulated the feeling of a hug. The researchers reported participants feeling joy and comfort from the haptic stimulation provided. Future research should systematically investigate the differences between the haptic stimulation provided in the present study and in the HaptiHug to determine if there were physical differences in the stimulation or if these differences in perception and interpretation of the stimulation could be driven entirely by the context of the experimental setting. Additionally, future explorations could benefit from more elaborate questions on the participants' subjective experience to further clarify the strategies and impressions of the users during the experiment.

5.3 Belt relative pressure

The relative pressure of the belt around the participant's torso was systematically manipulated throughout the experiment in blocks of three different relative pressures ($P_0, P_1 = P_0 * 140\%$, and $P_2 = P_0 * 180\%$). Our results showed that the tightening with P_1 and P_2 had a significantly greater effect on participants than the P_0 pressure. However, in their subjective impressions of the intensity of the haptic stimulation, the participants did not report a significant difference between the three different pressures. In addition, the first block of trials was rated as significantly less intense than the proceeding blocks of trials, independent of the applied pressure. This suggest that participants became more sensitive to the haptic stimulation as the experiment progressed, rather than habituating to the stimulation. The distance recorded however did not significantly evolve with time, which implies that the heightened sensitivity did not influence their behavior.

Sensitization to threatening or angry stimuli has been observed in other modalities. Strauss et al. [58] found that repeated presentation of angry faces led to them being rated as increasingly aversive, alongside increasing activity in the insula, cingulate, thalamus, basal ganglia, and hippocampus. This was in contrast to fearful, neutral, and happy faces, which did not reveal any sensitization. Similarly, Liu et al. [38] also found sensitization to angry faces and found this process to be affected by administration of oxytocin and inhibition of the serotonin system, suggesting a possible causal role of neurotransmitters in this sensitization. Finally, Bowman et al. [9] found that exposure to angry voices led to subsequent sounds being perceived as more angry and less fearful. Our results thus contribute to a growing body of work showing a unique learning process for angry or threatening stimuli of sensitization to repeated exposure. However, in our current study, we cannot exclude that the sensitization is a general response to haptic stimulation rather than an anger-specific one. Future research will have to address this specific question.

5.4 Social Interactions in VR

Our overall results suggest that including haptic stimulation in a virtual reality experience can significantly impact a person's perception of social interactions within that setting. While our results argue for the ability of haptics to negatively influence the perception of an interaction, our results also hint at the possibility of an opposite effect with haptics leading to a more positive interpretation of an interaction, as has been demonstrated in past research [59]. Our results on immersion and subjective perception also suggest that haptics do not need to have a biasing effect on experiences within virtual reality, but can instead be used to enhance the authenticity and accuracy of a person's perception. Utilizing haptic technologies in the future could lead to people engaging more closely and carefully with potentially dangerous situations, as well as getting greater satisfaction out of positive experiences. Weighted blankets and other somatosensory-related items have been shown to help with over-stimulation, especially in the case of both autistic children and adults [23]. A calm pressure via the haptic belt could help relax and focus on the contact to escape over-stimulation, from external stimuli or social interactions. Inversely from our experiment, a crowded space could become more bearable.

5.5 Limitations

In the virtual environment, participants were embodied as standing in the alleyway. However, in the laboratory, they were sitting down, while wearing the VR headset to limit fatigue during the experiment. This disparity between the real and virtual experiences may have affected the participants' experience of the virtual scenario, particularly their feeling of immersion. Nonetheless, since this difference in real and virtual posture was consistent throughout the experiment, it should not have had any effect on the results. Additionally, the participants being seated ensured that they did not physically move in response to the experimental paradigm, which would have created a further mismatch between the real and virtual experiences, since the virtual avatar always remained in the same position.

It is possible that the effects of the belt on participants' responses were not caused by a direct effect on the feelings of discomfort or threat. There may instead have been an effect of social desirability, where if the participants guessed the aim of the research, they may have pressed the response button sooner on the trials with the belt active, because that is what they thought was expected. Alternatively, the belt may simply have caused greater discomfort or annoyance for the participants, leading them to end a trial sooner. While, the significant interaction of the haptic activation and the avatar emotion, as well as the qualitative analysis of participants' responses argue against these explanations, they cannot be fully dismissed.

6 Conclusion

We investigated the perception of peripersonal spaces in simulated social VR combined with a compressive haptic device. We conducted a study wherein virtual agents approached participants in a dark alley; the agents emoted either anger or a neutral attitude, and the haptic device tightened around the participants' torsos for half of all trials. We asked users to stop the approaching agent by pressing a button when its proximity started to feel uncomfortable. Consistently with previous works, users exhibited 31% greater peripersonal space boundaries when the agent appeared angry and the belt activated. The more the belt tightened, the faster users felt uncomfortable, up to 13% when increasing the pressure. Our results underline the impact of social haptics during interpersonal interactions, and their potential use to mediate additional emotions in a virtual reality context.

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