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Warm regards: Influence of thermal haptic feedback during social interactions in VR

Jeanne Hecquard*
Inria, Univ Rennes, CNRS, IRISA
Claudio Pacchierotti†
CNRS, Univ Rennes, Inria, IRISA

Justine Saint-Aubert†
CNRS, Univ Rennes, Inria, IRISA
Anatole Lécuyer*
Inria, Univ Rennes, CNRS, IRISA

Ferran Argelaguet*
Inria, Univ Rennes, CNRS, IRISA
Marc J-M Macé†
CNRS, Univ Rennes, Inria, IRISA

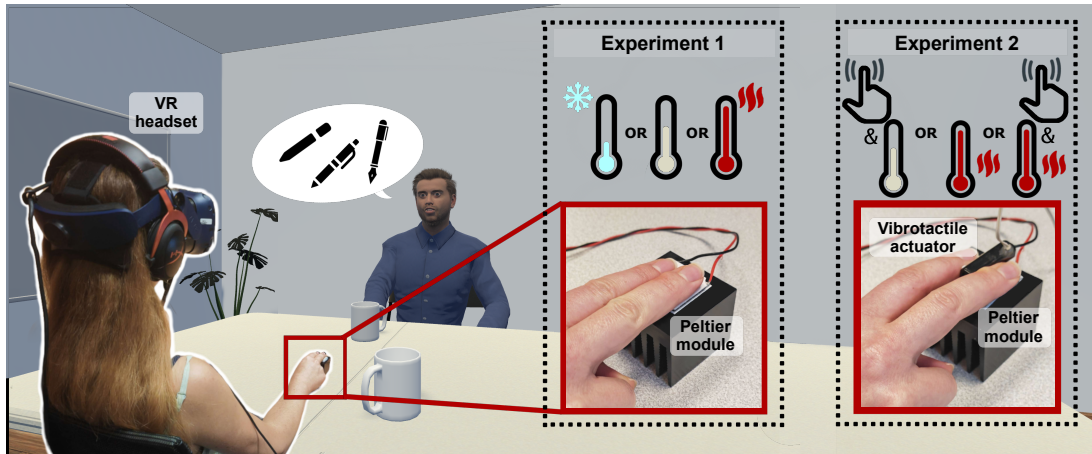


Figure 1: We studied the influence of thermal haptic feedback on several aspects of social interactions in VR, namely persuasion, focus, co-presence, and friendliness. Participants were immersed in a virtual meeting room and listened to a virtual agent for 3 minutes while receiving either warm, cool, or neutral feedback. The thermal feedback was delivered using a Peltier module on which participants rested two fingers. Results show that warmth positively affected persuasion and friendliness. In a second study, participants followed the same protocol while receiving thermal and vibrotactile feedback.

ABSTRACT

In this paper, we study how thermal haptic feedback can influence social interactions in virtual environments, with an emphasis on persuasion, focus, co-presence, and friendliness. Physical and social warmth have been repeatedly linked in psychological literature, which allows for speculations on the effect of thermal haptics on virtual social interactions. To that effect, we conducted a study on thermal feedback during simulated social interactions with a virtual agent. We tested three conditions: warm, cool, and neutral. Results showed that warm feedback positively influenced users' perception of the agent and significantly enhanced persuasion and thermal comfort. Multiple users reported the agent feeling less 'robotic' and more 'human' during the warm condition. Moreover, multiple studies have previously shown the potential of vibrotactile feedback for social interactions. A second study thus evaluated the combination of warmth and vibrations for social interactions. The study included the same protocol and three similar conditions: warmth, vibrations, and warm vibrations. Warmth was perceived as more friendly, while warm vibrations heightened the agent's virtual presence and persuasion. These results encourage the study of thermal haptics to support positive social interactions. Moreover, they suggest that some haptic feedback are more suited to certain types of social interactions and communication than others.

Keywords: Affective haptics, Thermal feedback, Virtual reality,

*e-mail: firstname.lastname@inria.fr

†e-mail: firstname.lastname@irisa.fr

Human Machine Interaction, Social Touch.

1 INTRODUCTION

Recent technological advancements have contributed to the increased use of immersive virtual environments (VE). As people seek novel and engaging ways to interact with digital environments, virtual reality (VR) allows popular platforms such as social networks to offer new, immersive experiences. Virtual social media platforms like VRChat¹ need better communication and moderation to prevent online harassment and echo chambers. It is crucial to have strong moderation mechanisms in place to ensure a safe and inclusive virtual environment for all users. While VR social media evolves, addressing these issues will be crucial for fostering a positive and responsible digital social landscape. One of the main concern is the lack of empathy and social proximity between users, most likely caused by anonymity and the gamified appearance of virtual avatars [8]. It thus stands to reason that working on social communication and empathy might enhance positively user interactions in social VEs.

To foster prosocial behavior in VR, there exist two main approaches. One focuses on the influence of avatar appearance and immersion into the VE to practice perspective-taking, via the Proteus effect [18, 54]. The other focuses on tactile feedback to convey emotions and empathy in a more physical way [19, 27, 48, 50]. This strategy aligns with what Crusco and Wetzel called the Midas touch effect [6]. A study on restaurants revealed that waitresses were better tipped by both male and female customers when lightly touching their arm. This phenomenon has been studied on multiple occasions since then and has even been shown to affect the perception of virtual avatars. Hoppe et al. [21] observed an increase in the perceived human

¹<https://hello.vrchat.com/>

likeness of avatars when simulating visually and haptically a light social touch from the avatar. The authors used a tangible haptic interface to recreate the tactile sensation of a hand on the shoulder. Such haptic devices used for social communication are called affective haptic devices. They mediate the communication of emotions through tactile feedback. A prominent example of affective touch is wearable devices that simulate hugs and contacts between two distant users [40, 47].

Affective devices foster positive emotions and help with communication and tone detection during social exchanges, virtually or otherwise. A significant part of affective haptics concerns the study of its potential impact on virtual contacts between users. Working on the sense of connectedness impacts users' capacity for empathy and compassion and can foster more positive social dynamics [23, 40, 48]. Vibrotactile feedback is a known method to enhance social presence and proximity. Despite that, some participants find it slightly uncomfortable or unpleasant [43]. This discomfort may affect its influence on participants, and different types of haptic feedback might be more effective depending on individual preferences. We chose to investigate thermal feedback's potential to enhance virtual social interactions.

Thermal feedback influences thermal comfort and, if correctly calibrated, is pleasant to most users [13]. Psychological literature heavily suggests a link between physical and social warmth. Social warmth, or interpersonal warmth, is defined as the feeling of social connection to others and the association of positive emotions with this feeling [24]. This theory, while not fully accepted, warrants further investigation. Warmth reportedly positively influences social proximity and behavior, provided the feedback is enjoyable [34]. If not, the effect is proportionally inverted [37]. These findings raise the question of the effectiveness of thermal feedback in social virtual interactions.

This paper aims to evaluate the potential impact of thermal feedback on virtual social communication, relying on social touch to create a sense of trust and friendliness in users [48]. This influence was also studied in comparison and in combination with vibrotactile feedback. To that effect, we devised two user experiments to test the influence of thermal feedback on user perception of virtual agents during simulated social interactions. Users exchanged with three virtual agents who aimed to change their minds on a specific subject. During each monologue, one of three haptic conditions was delivered: warmth, cool, or neutral. For the second experiment, the haptic conditions changed to warmth, vibrations, and warm + vibrations. After overviewing the literature, Experiment 1 on social thermal feedback will be presented, followed by Experiment 2 on the combination of thermal and vibrotactile feedback in a similar context. The last sections will include a discussion of our results, and a conclusion on our initial hypotheses.

2 RELATED WORKS

2.1 Affective haptic feedback

Affective haptics focuses on transmitting, enhancing, or influencing emotions via touch sensations. One of the most common types of affective haptics is mediated social touch, i.e., using hugs or caresses as a mean to convey affection and relaxation during human-human interaction [40]. In this paper, we study social touch during virtual communication; we aim to positively influence user perception of virtual agents while increasing their persuadability.

2.1.1 Influence of haptic feedback on persuasion and focus

Slater et al. [44] studied the correlation between the sense of presence in a virtual environment and the perceived leadership of the participants. In the experiment, participants designated a leader after a group exercise in a virtual environment. The participant with the highest immersion was also the one most subsequently chosen as leader. As Saint-Aubert et al. [43] highlighted, haptic feedback has been shown to positively affect the sense of presence, and may thus similarly influence leadership. Saint-Aubert et al. [43] investigated vibrotactile feedback to augment virtual verbal interactions in VR.

Vibrations reinforced the speech of both virtual agents and users. The feedback was inferred from the audio files, resulting in vibrations synchronized with the agents' voices. Results showed that the feelings of persuasion, leadership, and co-presence significantly increased with vibrations. While vibrotactile feedback has been shown to positively enhance social connections, it might be too noticeable and seen as aggressive. A more subtle feedback might also be efficient while feeling more pleasant to users. Valori et al. [48] reviewed means of social interactions via social touch and evocations of social touch (i.e. interpersonal behavior). The authors highlighted the impact of social touch on the perceived trustworthiness of an interlocutor, which they found to be reciprocal: the perception of trust influenced user behavior and increased interpersonal behavior such as social touch.

2.1.2 Influence of haptic feedback on co-presence

Affective touch seems correlated to the feeling of co-presence: its main goal is, in itself, to heighten "togetherness" between individuals [20]. This feeling of co-presence is bilateral: individuals can feel that their partner is more present with them, but they can also feel that their partner perceives them as more present themselves. In this regard, hugs, kisses, or handshakes can constitute a way to enhance co-presence. As for discriminative touch, vibrotactile feedback appears to enhance feelings of presence [11] and social presence [15]. This includes co-presence, which is a sub-part of social presence [39]. Banakou et al. [4] studied the effect of speech-based vibrations on embodiment, the feeling that your virtual body is your own, which has also been correlated with social presence and co-presence [45]. Saint-Aubert et al. [43] demonstrated the influence of vibrotactile feedback on the feeling of co-presence. This phenomenon seems to be partially unilateral: when enhancing the voice of the agent speaking, participants only felt an improvement in the agent's presence, as opposed to the agent's perception of the participants. On the other hand, when enhancing the participants' voices, both bilateral feelings of co-presence significantly increased.

2.2 Influence of thermal touch

2.2.1 Interpersonal warmth

Ijzerman et al. [26] presented the term "social thermoregulation" as an explanation of human social dynamics. The theory is that human relationships are centered around body temperature regulation. The need for affiliation would in part come from physical body temperature, and in turn, could help regulate these social emotions. When physically cold, people feel more easily lonely [28]. This need for social contact could therefore be somewhat compensated by physical warmth.

Moreover, thermal feedback could be used to convey affect [13]. Combined with pressure and vibrotactile feedback, thermal feedback could depict emotions in text messages, helping with tone detection that would usually be expressed with emojis or images [9, 32]. A common use of vibrations with thermal feedback is for the communication of emotions [33]. Emotions are represented here on a two-dimension graph called the model of affect: the two axes are called valence and arousal. Valence is defined by Russel et al. [42] as the level of pleasantness generated by an emotion, ranging from misery (low) to pleasant (high). Arousal is the level of excitement of this emotion, from calm (low) to excited (high). Without vibrations, thermal feedback can also express a wide variety of emotions [53]. Mostly, warmth can be perceived as either high valence, low arousal (comfort), or inversely as low valence, high arousal (anger). The rate of temperature change mattered most, as a slow, low-temperature change was rated as most pleasant. Extrapolating from these results, some researchers studied the augmentation of voice in social contexts [16]. For example, Ali et al. [7] used thermal wear in combination with neutral-sounding voices to influence the perceived valence and arousal of the messages. Seeing that physical temperature influences interpersonal warmth, it raises the question of which specific emotions and interactions can be influenced in that regard.

2.2.2 Influence of thermal feedback on trust and prosocial behaviour

The theory of social thermoregulation, and thereafter the fact that thermal feedback affects persuasion, is not universally accepted. While Williams et al. [52] previously proposed that thermal sensations affect interpersonal warmth in social interactions, recent results disputed it. Willemse et al. [51] and Krause et al. [29] both recently refuted the concept of social warmth created from physical warmth in 2018 and 2023, respectively. Lynott et al. [31] also disputed it in 2023 with a review of the literature. The authors argued that previous studies either had too many biases or that the experimental protocols were not rigorous enough for such affirmations. One of Lynott et al.'s main criticisms of such studies was the lack of within-participants protocols, with few participants, and a lack of diversity in age ranges. A study focused on comparisons made by the same participants would allow for a sturdier analysis. While this paper is critical of the previous literature, this does not impede our work, as most of the disputed papers were on social warmth, as opposed to focus or persuasion. In fact, recent studies on the influence of thermal feedback showed that warmth increases relaxation and inherent trust [22, 48].

This influence does not remain limited to social interactions. Thermal comfort has long been studied in the construction and commercial industries, as a way to comfort customers and encourage consumption [49]. Yoo et al. [55] highlighted increased sales during extreme weather conditions in Seoul, Korea. This effect was hypothesized to stem from the weather's influence on temperature, fostering thermal comfort-seeking behavior in customers [35, 41]. The authors theorized that the increase in consumption might be caused by the relief of the thermal comfort experienced when leaving the extreme heat and stepping into a cool place.

Warmth could also help foster trust and relaxation. Hornstein et al. [22] studied the inhibition of Pavlovian fear responses via thermal feedback. Participants were led to associate props presented to them with small electric shocks. Some of those objects were activated warm packs. Results showed that the warmth successfully inhibited the fear response in participants, as opposed to the neutral objects. Warmth was validated as a perceived safety stimulus, whereby participants felt more secure and trusting of the objects presented. This correlates with other studies on the influence of physical warmth on social trust [34]. Cold temperatures, by contrast, seem to decrease empathy, fostering cognitive and 'cold-hearted' thinking instead [1, 46]. Participants would become "cold-hearted" [12, 36] and think in a more self-centered way [14]. Luo et al. [30] observed increased racial in-group bias when exposed to cold temperatures. Participants experienced larger empathic neural responses when looking at painful facial expressions of individuals of the same ethnic group than when looking at faces from other ethnicities. This theory suggests that cool feedback would negatively influence persuasion and co-presence but might enhance the participant's ability to focus on social exchange.

2.2.3 Influence of thermal feedback on social presence

To our knowledge, there is no work studying the influence of thermal feedback on co-presence in virtual environments. Gooch et al. [13] experimented with warm hugs for social presence. Participants reported an increase in perceived social presence when hugged while receiving warm thermal feedback, as opposed to not being hugged. They, however, did not consider delivering warm, cool, or neutral hugs, limiting the broadness of their results. In the experiment conducted by Ijzerman et al. [25], Participants reported feeling personally closer to the physically warm agent, and felt more distant from the cool agent. Haliburton et al. [16] proved thermal feedback to increase social connectedness between presenters and their audience. A small thermoelectric cell strapped to their wrist communicated the audience's interest in the presentation: cold meant disinterest and warmth meant active interest. Participants reported heightened feelings of awareness and connection to the audience when receiving warm feedback.

While to our knowledge, warmth has not been studied for co-presence, these results show that thermal touch is a promising technique for influencing the perception of social and spatial proximity, notably during virtual social interactions.

3 EXPERIMENT 1: THERMAL SOCIAL FEEDBACK

The first experiment aimed at determining if thermal feedback can influence feelings of trust and social proximity of users as a review of the literature suggested. To expand on this theory, this study focused on the feelings of persuasion, focus, and co-presence of users when faced with virtual agents trying to convince them. Volunteers evaluated the influence of thermal feedback on the convincingness of the agents' speeches, wherein 3 agents separately tried to convince users that they were the right one. For each agent, a different thermal feedback was given: cool, warm, or neutral. The 3 conditions aimed to verify the theory commonly exposed in the literature: that warmth would positively influence the interaction between users and the virtual agent, as opposed to neutral or cool feedback. Particular interest was given to the influence of the feedback on user decisions: would users have their minds changed by an agent's speech, and if so would that speech be supported by warm feedback? This question rests on the persuasive effect of the virtual agent.

3.1 Experimental Protocol

Participants sat in a virtual meeting using a head-mounted display and embodying a first-person gender-matched avatar. They went through the scenario 3 times with the same male agent facing them while seated at a table. Using slightly different avatars for each agent might have raised bias issues over user perception, adding another variable to the experiment. The sequence of events is summarized in Figure 2. Each time, the agent would monologue for 3 minutes on which type of pen was the best to write with. The three monologue themes were fountain pens, roller pens, and erasable pens.

During each monologue of 3 minutes, the participants continuously received one out of three possible thermal feedback: cool ($26.0 \pm 2.3^\circ\text{C}$), warm ($38.5 \pm 2.7^\circ\text{C}$), and neutral ($32.0 \pm 0.5^\circ\text{C}$). Thermoception is known to differ between users, depending on their initial thermal comfort, skin temperature, and skin condition [5], which justifies such variations in calibration. As for the neutral condition, the Peltier cells were barely turned on, which favored the users' skin in terms of thermodynamics. We determined the order in which they received the three feedback with a Latin square. In doing so, we created three groups of ten participants: Warm-Cool-Neutral, Neutral-Warm-Cool, and Cool-Neutral-Warm. All participants tested each condition: warm, cool, and neutral. A randomizer separately determined the order of the haptic feedback and of the agent's monologue (on fountain, roller, or erasable pen). No feedback condition was associated with a monologue subject.

Before beginning the experiment, we conducted a calibration process: the participants received all three thermal feedback and rated them from 1 (too cold) to 7 (too hot). This allowed to verify that each participant felt the warm feedback was between 5 (warm) and 6 (hot), the cool feedback between 2 (cold) and 3 (cool), and the neutral at 4 (neutral). The process went as such: the neutral feedback was first so as not to taint it with the other sensations. Then, the warm feedback, followed by the cool. The experimenter highlighted that each feedback should be distinctly perceivable but not uncomfortable. If one of the three test sensations was deemed too hot or cold, the experimenter turned the intensity of the thermal device down. Similarly, the intensity could be turned up.

Between each touch (calibration and experiment), participants removed their hands from the thermal device to allow their skin temperature to get back to normal. Similarly, the thermal device went into 'neutral' mode after each calibrating touch and between the three monologues. A laser thermometer measured their fingertip

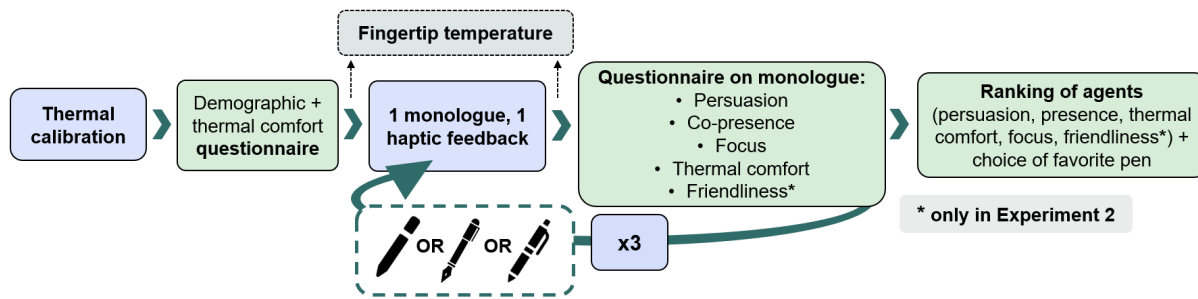


Figure 2: Experimental design. In Experiment 1, participants received thermal feedback via a Peltier module whereon they rested two fingers. They went through 3 scenarios, during which they randomly received different feedback: warmth, cool, or neutral. In Experiment 2, the conditions were changed to warmth, vibrations, or both (warmth + vibrations). For each condition, they listened to a virtual agent speak on a subject chosen at random: fountain pens, roller pens, and erasable pens. After each condition, they reported their perception of the agent using Likert scales. After all conditions, they compared the 3 speeches and chose their favorite pen to write with.

temperature at the end of each questionnaire. The waiting period and this additional measure verified that their fingers had cooled or warmed to 0.5°C of their usual temperature (on average between 28 and 31°C) before starting the next simulation.

At the end of each simulation, they rated the agent based on their sense of co-presence, persuasion, thermal comfort, and focus on the agent. After participants went through all three conditions, they were asked to rank the agents in order according to their perceived persuasion, focus, co-presence, and thermal comfort. After the experiment, users were led to choose the agent who ‘changed their mind’. An additional option provided ‘No preference’ as an answer.

In total, the experiment lasted between 25 and 40 minutes. The experimental protocol was approved by the local ethical committee.

3.2 Hypotheses

According to the literature, physical warmth can foster artificial interpersonal warmth and feelings of trust. It also affects decision-making. On the other hand, cool feedback heightens ‘cold-headed’ thinking and can influence the ability to focus, which can, in turn, influence persuasion. Building on these results, we elaborated three hypotheses for the results of the first experiment:

- **H1.1:** Both thermal feedback influence persuasion
 - **H1.1a:** Warm feedback enhances persuasion
 - **H1.1b:** Cool feedback diminishes persuasion
- **H1.2:** Warm feedback enhances co-presence
- **H1.3:** Cool feedback enhances focus

3.3 Apparatus

3.3.1 VR environment

The virtual environment was a virtual meeting room, including a table where the participant and the agents sat. The VR head-mounted display was a HTC Vive Pro. The orientation of the embodied avatar’s head was controlled by the orientation of the head-mounted display inferred by two lighthouses. The full experiment set-up is visible in Figure 1.

3.3.2 Monologues

We selected the topic of the monologues based on how uncontroversial it was. This choice relied on the assumption that ‘which kind of pen is the best to write with, in any given context’ would not be too meaningful for most people. While they may have a preference, they may stay open to hearing out the agents defending the other pens and would not be too biased. It also allowed for three or more opinions on the subject, as many as there are pen types. Thus, each agent got

a three-minute speech on the writing qualities of a specific type of pen. They defended fountain, ballpoint, or erasable pens.

ChatGPT² was used to generate the speeches in a similar manner, so they would end up with comparable arguments for the different pens. With this, each monologue sounds alike enough to the others that it could almost argue for the other pen types. For example, each speech talks about how versatile their pen is: the fountain pen can ‘switch between colors easily’, ballpoint pens are ‘super variable’, and ‘erasable pens come in a spectrum of colors’. The generated texts were then slightly corrected and translated to our native language, French. This allowed volunteers an easier understanding of the speech content. A Text-to-Speech online converter rendered them into audio speeches³. All agents had the same voice, with a peak pitch of 150 Hz. We used Oculus lip sync in Unity3D on the avatars to display their lip movements.

3.3.3 Thermal feedback

Thermal feedback was rendered using a 30x30x4 mm thermoelectric Peltier module. It was controlled by an Arduino via a 2 A DRV8838 single brushed DC driver card, and powered by a 5 V electric charger. A 50x50x40 mm, 3.1 K/W heatsink was attached to its side using thermal glue. This approach allowed for precise feedback control with swift diffusion of the module’s side opposed to the user. During both experiments, the thermal feedback stayed at a constant temperature determined by user calibration and the haptic condition. The temperature did not change during the agents’ speeches and was verified before the start of each speech. Constant thermal feedback was chosen for two main reasons. First, possible dynamic renderings would be hindered, by both the technical limitations of Peltier cells and the human skin’s thermal sensors. While bursts of thermal feedback would be feasible, they would need to be slowed down to a technically doable and thermally perceivable rate. This fact limits simple applications such as modulating the temperature according to the agent’s voice. Moreover, prior works on social warmth mostly used constant feedback, whether via hot pockets or ambient temperature [48]. To translate this effect in virtual environments, we chose similar thermal feedback with a small contact area. Although fingertips are slower in thermal perception than the palm, a few additional seconds are not substantial compared to the entire duration of the conditions. This location also allows easier skin contact on the device. Users reported a good perception of the thermal feedback throughout the 3-minute conditions.

²<https://chat.openai.com/>

³<https://genny.lovo.ai/website>

3.3.4 Audio Feedback

Audio feedback was produced by an Nvidia HD Audio computer sound card and transmitted through a Hyper X Cloud noise isolation headset. The sound was displayed in Unity via an audio source at the speaking agent’s mouth, with participants having an audio listener attached to their avatars. We used similar technical settings and devices as in a previous study [43]; all parameters of the audio source were set to their default values. The audio level was set to a comfortable level for the user, and all characteristics were selected for maximum comfort (volume = 13dB, threshold = -12.5dB, ratio = 722%, attack time / release time = 100 ms, make up gain = 0dB, knee = 13dB, side chain mix = 0%, Windows audio level = 14).

3.4 Experimental design and conditions

3.4.1 Evaluation criteria and metrics

Prior to the experiment, we collected standard demographic measures (age, gender) and technical experience, then measured fingertip temperature. After each condition, participants completed a questionnaire on persuasion, co-presence, thermal comfort, and focus. Fingertip temperature was again measured to account for perception bias and verify that the temperature would revert to its baseline before next condition. Questions on persuasion and co-presence were respectively taken from previous studies by Hanus et al. [17] and Bailenson et al. [3]. Users rated their thermal perception using two 7-point Likert scales: the ASHRAE 7-point thermal sensation scale [2], and the thermal satisfaction, or thermal comfort scale [10].

- **Q1.1** With regard to the current temperature of the room and of your body, how do you feel right now? - Hot (1) to Cold (7)
- **Q1.2** How satisfied are you with the current temperature of the room and of your own body? - Very satisfied (1) to Very unsatisfied (7)

The questions related solely to the virtual scene were also rated on 7-point Likert scales, from Fully disagree (1) to Fully agree (7): "When I was listening to the agent, I felt that..."

- **Q1.3** the agent was convincing. (Persuasion)
- **Q1.4** the agent was in the room with me (Agent Presence)
- **Q1.5** the agent was aware of my presence. (Agent Awareness)
- **Q1.6** I remained focused on the agent while he was talking (Focus)

Q1.4 and **5** specifically investigated participants’ sense of co-presence with the virtual agent.

After the experiments, users ranked the agents in a tier list according to the previous questions: co-presence, persuasion, focus, and thermal comfort. They also expressed their preferences in terms of pens (fountain, roller, erasable, or no preference/other) both before and after the experiment. This behavioral measure allowed to check if the experiment had swayed their opinion in any way, an additional evaluation of the agents’ convincingness.

3.4.2 Subjects

A total of 30 volunteers participated in the first experiment (20 men, mean age: 29.9 ± 8.9 years). The experiment’s participants all gave written informed consent and did not receive any form of compensation. None reported any impairments that would have impacted the experiment, including those related to vision, hearing, or touch. Of the total, 14% had never tried VR, 64% had tried it, and 22% worked in the XR field. User demographic data did not significantly influence the reported and behavioral measures. Participant skin temperature averaged to $30.8 \pm 3.3^\circ\text{C}$ at the start of the experiment, and $31.7 \pm 2.6^\circ\text{C}$ at its end.

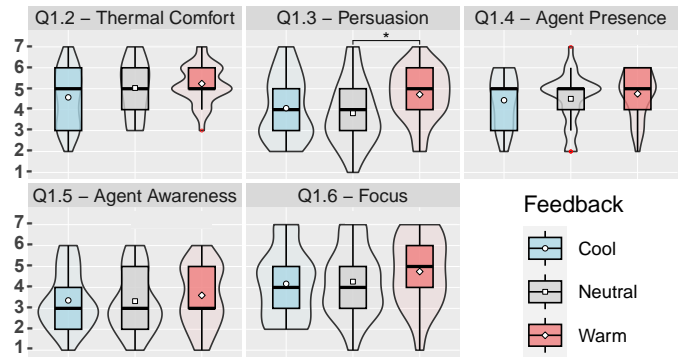


Figure 3: Experiment 1: Likert scales of user opinions for each feedback condition. Boxplots visualize medians and dispersions, white squares represent means. * means ($p < 0.05$).

3.5 Results

3.5.1 Likert scales from each condition

The results for the Likert scales are reported in Fig. 3. The normality assumption was not met for most of the data. We then analyzed the data using the Friedman test. Bonferroni correction was applied to the p-values to account for multiple comparisons. If a significant effect was found, a post-hoc analysis via the Wilcoxon Signed-Rank test was performed to check the significance of the pairwise comparisons. Spearman’s rank correlation assessed relationships between variables.

A significant effect of the thermal feedback on the thermal sensation (Q1.1) was found ($p < 0.0001$, $\chi^2 = 32.4$). Initial thermal comfort of the room was ranked 5.3 ± 1.2 , “Slightly Comfortable”. The warm feedback was perceived as significantly warmer than the neutral ($p < 0.0001$, $r = 0.70$) and cool feedback ($p < 0.0001$, $r = 0.76$). The thermal feedback also had a significant effect on the participants’ thermal comfort (Q1.2, $p < 0.05$, $\chi^2 = 8.6$) but comparisons did not reveal a significant effect between pairs.

A significant effect of the thermal feedback on the persuasion was found (Q1.3, $p < 0.01$, $\chi^2 = 9.4$). The participants’ impression that the agent was convincing was significantly higher with warm feedback than with neutral feedback ($p < 0.05$, $r = 0.51$).

Thermal feedback had no significant effect on focus (Q1.6, $p = 0.10$, $\chi^2 = 4.6$) and co-presence (Q1.4&5, $p = 0.33$, $\chi^2 = 2.3$) or agent presence (Q1.5, $p = 0.40$, $\chi^2 = 1.9$). The order of presentation of the thermal feedback also had no significant effect on the results, except for the co-presence, which decreased with time ($p < 0.05$, $\chi^2 = 7.2$). Since different monologues were randomly used for each condition, we also tested their effect. The theme and order of the monologues had no significant effect on user self-reports.

3.5.2 Final comparisons

Figure 4 summarizes the final rankings of each participant regarding the 3 conditions. 49% of participants ranked the ‘warm’ agent as being the most persuasive, and 45% found the ‘cool’ agent to be the least persuasive. Thermal comfort and focus were similarly ranked with ‘warm’ agents being slightly preferred, if slightly less so for the focus. Additionally, 30% (9 out of 30) of participants changed their mind on their favorite pen. These choices are visualized in Figure 5. Of those, 88.9% (8 out of 9) did so in favor of the ‘warm’ pen: the one presented by an agent while receiving warm feedback. In total, 60% (18 out of 30) of the favorite pens chosen by users were presented during the warm condition, regardless of their previous preferences.

3.6 Conclusion of Experiment 1

Our hypotheses on warmth perception were mostly supported: warm feedback enhanced persuasion, while cool feedback did not

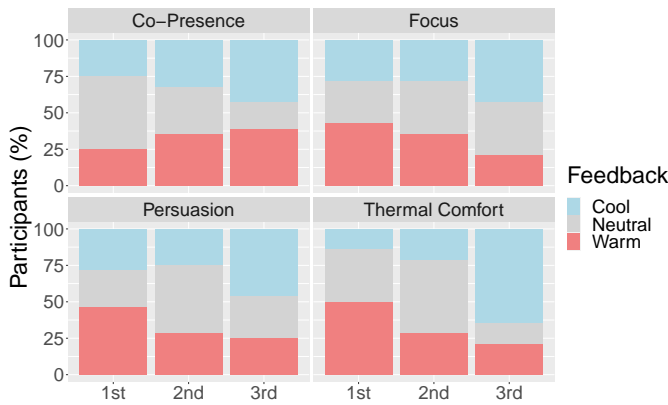


Figure 4: Experiment 1: User preferences for each condition, ordered by rank: 1st, 2nd, 3rd best.

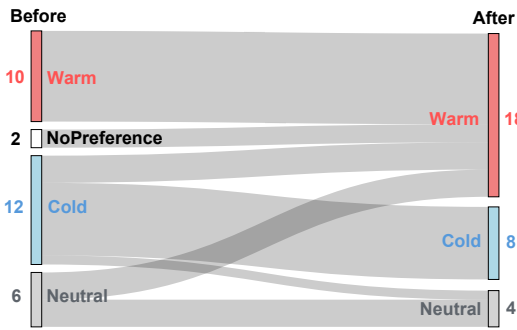


Figure 5: Experiment 1: Sankey diagram of pen preferences with regard to the feedback received: Before vs. After experiment. Users chose their favorite pen to write with, which was associated with the feedback received during the experiment for visualization purposes.

significantly influence focus or persuasion. Thermal feedback did not have any significant effect on co-presence. Additionally, 5 different users reported increased feelings of perceived social warmth from the agents when receiving warm feedback. Three of them stated that the otherwise robotic voice sounded and felt more human when receiving warm feedback. These comments suggested the addition of a new dimension in the questionnaires: the evaluation of the perceived friendliness of the agent. The results also raised the question of the influence of warmth and vibrations used in tandem. Having shown that warm feedback is a valid way of augmenting social interactions, a second study adding vibrotactile feedback would allow further validation. We could for instance, see if a combination of both feedback would heighten or decrease co-presence or focus.

4 EXPERIMENT 2: THERMAL AND VIBROTACTILE SOCIAL FEEDBACK

4.1 Experimental design

The experimental design for this experiment was taken directly from Experiment 1. A total of 30 different volunteers went through the same three scenarios, for three minutes each. For each scenario, instead of only thermal feedback, we used warm feedback (Experiment 1's best-ranked feedback), vibrotactile feedback, and a combination of both (warm + vibrations). Our local ethical comity approved the protocol, visualized in Figure 2.

4.2 Hypotheses

From the first experiment, we gathered that warmth positively influenced the agents' persuasion. However, this influence, although not comparable, did not seem to be as strong as the one from Saint-Aubert et al. [43]'s results of vibrations on persuasion and co-presence. Participants also reported after the experiment that the 'warm' agents felt more human and friendly than the others. In light of this, we elaborated these hypotheses for the results of the second experiment:

- **H2.1:** Both vibrotactile and warm feedback enhance persuasion and will do best when combined
- **H2.2:** Vibrations enhance focus and co-presence, and warm + vibrations enhance focus the most
- **H2.3:** Warm feedback enhances the perceived friendliness

4.3 Apparatus: Vibrotactile feedback

The apparatus was almost the same as in Experiment 1 (cf Figure 1). The vibrotactile feedback we added was set up and delivered in the same way as a previous study on persuasive vibrations [43]: using speech-to-touch to enhance the agents' voices. From multisensory perception knowledge, we hypothesized that the haptic feedback would be better integrated if it is congruent with audio feedback. Another type of signal, e.g., a constant frequency without envelope, could draw the user's attention away from the verbal interaction. Such feedback was found efficient by Saint-Aubert et al. [43], positively influencing the perceived leadership and co-presence of virtual agents.

Vibrotactile feedback was delivered by a HapCoil actuator from Actronika (France). It is a small cylinder of 3.5 cm height and 1 cm radius, and one of the best actuators to cover the haptic bandwidth of vibrations. The audio bandwidth is larger than the haptic one, but vibrations outside the haptic bandwidth would not be perceived by users, so it should not significantly impact users' experience. We controlled amplitude and frequency and its bandwidth of 10Hz to 1000Hz covered the haptic band and most of the audio band. The bandwidth of the HapCoil allows us to display the most important frequencies of human voices (around 100-150Hz for men and 200-300Hz for women) [38]. A single to dual jack splits the audio output into two identical signals, one for the headphones and one for the vibrotactile actuator. A relay module activated or deactivated the actuator. The audio signal was amplified by a digital amplifier board powered by a power supply. The signal was not processed to directly obtain the corresponding vibrations. An annexed file contains some spectrum and waveforms as visual representations of the audio and haptic feedback (the actuator's output). During the 'warm' condition, where vibrations were not rendered, the actuator stayed in place between the participants' fingers but was not activated.

4.4 Experimental protocol and conditions

4.4.1 Evaluation criteria and metrics

We used the same protocol and questions as in Experiment 1 on persuasion, co-presence, thermal comfort and focus. This included a calibration of the warm and neutral thermal feedback conditions for each participant. The main differences were the conditions: warm, vibrations, warm + vibrations, as well as one additional question per condition: the perceived friendliness of the agent: **Q2.7** I felt that the agent was friendly - Fully disagree (1) to Fully agree (7).

After the whole experiment, users ranked in order the agents based on how friendly they were, on top of the rankings (persuasion, co-presence, thermal comfort, and focus) and the choice of favorite pen from Experiment 1. They also filled 7-point Likert scales on the pleasantness and easiness of perception for each feedback: When receiving the feedback, I felt that... - Fully disagree (1) to Fully agree (7)

- The vibrations (warmth) were easy to perceive
- The vibrations (warmth) were pleasant to the touch

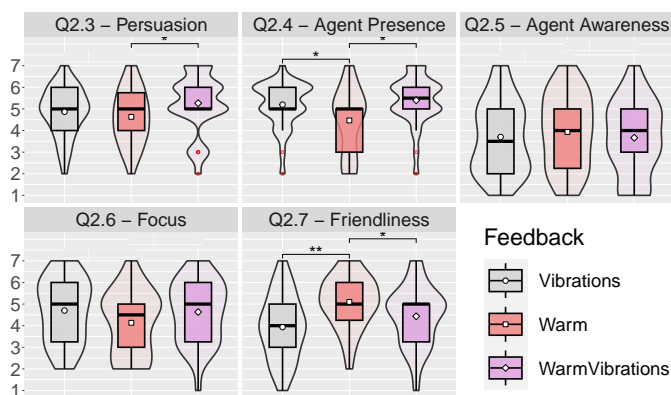


Figure 6: Experiment 2: Likert scales of user opinions for each feedback condition. Boxplots visualize medians and dispersions, white squares represent means. * means ($p < 0.05$) and ** means ($p < 0.01$).

4.4.2 Subjects

A total of 30 volunteers participated in the second experiment (19 men, mean age: 29.0 ± 9.8 years). They were not the same participants as Experiment 1. They all gave written informed consent and did not receive any form of compensation. None reported any impairments that would have impacted the experiment, including those related to vision, hearing, or touch. 10% had never tried VR, 70% had tried it, and 20% worked in the XR field. User demographic data did not significantly influence the reported and behavioral measures.

All participants tested each condition: warm, cool, and neutral. A randomizer separately determined the order of the haptic feedback and of the agent’s monologue (fountain, roller, or erasable pen). No feedback condition was associated with a monologue subject. Participant skin temperature averaged $29.8 \pm 5.1^\circ\text{C}$ at the start of the experiment, and $30.4 \pm 3.9^\circ\text{C}$ at its end.

4.5 Results

4.5.1 Users opinion on each condition

The results for the Likert scales are reported in Fig. 6. We used the same procedure as in Experiment 1 to analyze the data.

A significant effect of the thermal feedback on the perceived temperature (Q2.1) was found ($p < 0.01$, $\chi^2 = 9.5$). In a physical sense, the warm feedback was perceived as significantly warmer than the vibrations ($p < 0.05$, $r = 0.32$), but the warm + vibrations were not. The haptic feedback did not have any significant effect on the participants’ thermal comfort (Q2.2, $p = 0.8$, $\chi^2 = 0.33$). Initial thermal comfort of the room was ranked 5.2 ± 1.4 , “Slightly Comfortable”.

Persuasion was significantly influenced by the feedback ($p = 0.01$, $\chi^2 = 8.9$). The participants’ impression that the agent was convincing (Q2.3) was significantly higher with warm + vibrations than with only warm feedback ($p < 0.05$, $r = 0.39$). Thermal feedback significantly influenced perceived friendliness (Q2.7) ($p < 0.01$, $\chi^2 = 11.1$), with warmth having a higher influence than vibrations ($p < 0.005$, $r = 0.47$). Haptic feedback had no significant effect on focus (Q2.6, $p = 0.2$, $\chi^2 = 3.2$) and co-presence (Q2.4&5, $p = 0.07$, $\chi^2 = 5.4$). It however significantly influenced the perceived agent presence (Q2.4, $p < 0.001$, $\chi^2 = 16.1$). Vibrations and warm + vibrations both tested a higher effect than warmth ($p < 0.05$, $r = 0.33$ and $p < 0.01$, $r = 0.38$). The theme and order of the monologues had no significant effect on user self-reports.

4.5.2 Final comparisons

Figure 7 visualizes the final rankings of each participant concerning the three conditions. 53% of participants ranked warm + vibrations as the most persuasive, and 60% found the vibrations alone to be

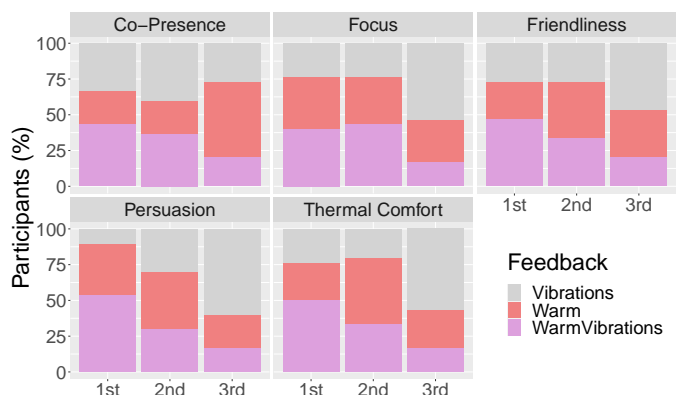


Figure 7: Experiment 2: user preferences for each condition, ordered by rank: 1st, 2nd, 3rd best.

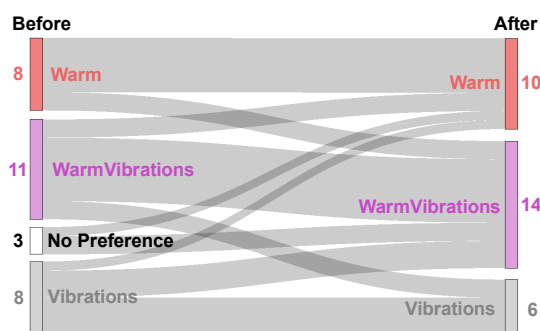


Figure 8: Experiment 2: Sankey diagram of pen preferences with regard to the feedback received: Before vs. After experiment. Users chose their favorite pen to write with, which was associated with the feedback received during the experiment for visualization purposes.

the least persuasive. Thermal comfort, Friendliness, and Focus also highlighted an overall preference for warm + vibrations. Users preferred vibrations for the Co-presence, and 53% found warmth to be the least effective. Participants reported thermal feedback to be more pleasant to the touch than vibrotactile feedback ($p < 0.05$, $med_t = 6$, $sd_t = 1.33$, $med_v = 6$, $sd_v = 1.72$). Here, t refers to the thermal feedback, and v to the vibrations. Both feedback were ranked as easy to perceive ($med_t = med_v = 7$, $sd_t = 0.85$, $sd_v = 0.35$).

Figure 8 illustrates users’ preferences in pens with regard to the feedback they received. Overall, 40% of participants (12/30) changed their minds, over half of them for warm + vibrations (23.3%). Eventually, most participants changed their minds for or kept the ‘warm + vibrations’ pen as their favorite (46.6%). The pens presented while receiving vibrations were the least chosen, regardless of previous preferences (23.4%).

4.6 Conclusion of Experiment 2

Our hypotheses were mostly supported by the results: warmth showed higher levels of perceived friendliness, and warm + vibrations had a greater influence on persuasion and co-presence. An analysis of the relationship between these variables returned that friendliness and persuasion, when linked by warmth, have a high correlation, while focus and persuasion worked better when linked by vibrations.

5 DISCUSSION

5.1 Analysis of our hypotheses

5.1.1 Influence of haptics on persuasion

In Experiment 1, we hypothesized that thermal feedback would have an influence on persuasion: Warm feedback would enhance persuasion, and cool feedback would decrease it (H1.1). Warmth's positive influence was supported by self-reports of each condition and the final ranking of user preferences. The negative influence of coldness was only partially supported by the results. While cool feedback was ranked last for persuasion in the final comparisons, the self-report of all conditions was not significantly below the neutral and warm ones.

H2.1 focused on the influence of haptic feedback on persuasion. We proposed that both vibrotactile and thermal feedback would enhance persuasion and that a combination of both feedback would work best. Overall, H2.1 was mostly validated. The first part was previously validated both by Experiment 1 and a previous study [43]. The self-report for each condition also supported it, with all three conditions having a persuasion level significantly superior to 'Indifferent' (4 on the 7-Likert scale). There was no significant difference between warmth and vibrations for the self-reports, and users ranked warmth as better than vibrations for persuasion. The expected heightened influence of warm + vibrations was fully validated: both final comparisons and self-reports ranked warm + vibrations as significantly better than warm feedback. This supports the effect of vibrations as there was no significant difference between the 'Persuasion' evaluation of warm + vibrations and vibrations alone.

5.1.2 Influence of haptics on focus and co-presence

H1.2 posited that warm feedback would enhance the co-presence felt by users. Although a slight trend was noted in favor of the hypothesis, no significant correlation was found. The neutral condition was also chosen most of the time for the condition with the best co-presence, while the warm feedback was mostly ranked second and third. H1.3 implied that cool feedback would enhance the users' capacity to focus. This hypothesis was not validated as the warm feedback significantly heightened the focus instead. Cool feedback was also ranked the least favored in terms of focus (Figure 4).

H2.2 stated that haptic feedback would influence focus and co-presence. We posited that vibrations would enhance both focus and co-presence, and that warm + vibrations would increase focus even further. The vibrations' effect was only partially supported for co-presence. Vibrations were ranked significantly better than warmth alone, and the agent were reported as significantly more present with vibrations than with warm feedback. For focus however, warmth was ranked better, and the self-reports revealed no significant difference. Warm + vibrations were also partially impactful: they were ranked as significantly different from vibrations only in the self-reports, and the final rankings revealed such preference for co-presence.

5.1.3 Influence of haptics on friendliness

In Experiment 2, H2.3 centered on users' perception of the agent's friendliness. Warmth would lead to higher levels of perceived friendliness. This hypothesis was mostly validated by the self-reports and the final rankings of the conditions. Warmth led to significantly higher friendliness than the others. Warmth was also mostly ranked first and second for friendliness, while vibrations were mostly ranked third. The results allow us to conclude that warmth has much potential as a social haptic feedback: it rated systematically better than cool and neutral feedback on Persuasion, Thermal Comfort, and Focus indicators, as well as in the rankings of conditions. In Experiment 2, the conditions with warm thermal feedback particularly increased the perceived persuasion and friendliness of the agents.

5.2 General discussion and perspectives

The two studies revealed an effect of warmth on virtual perception of speech; users reported an increase in perceived persuasion and friendliness. This report is coherent with the existing literature on social thermoregulation, which states that more comfortable temperatures could positively influence social interactions [24]. Saint-Aubert et al. [43] observed similar results for vibrotactile feedback. In the present work, we demonstrate that a combination of both feedback is appropriate and as efficient, if not more efficient than each feedback alone. Vibrations and warmth raised persuasion, but warm + vibrations had a more intense effect. Such combination of feedback could help foster empathy and conflict resolution. In appropriate contexts, thermal feedback could diminish negative feelings, help users relax during tense situations, or push for perspective-taking.

These two experiments aimed to uncover any influence of thermal feedback on social interactions. We aimed for the simplest type of feedback with a small contact area. Since such a small scale sufficed to have an impact, a future reproduction of this experiment could integrate Peltier cells in VR controllers or other small, portable devices. Significant effects were observed despite the tactile area staying limited to users' fingertips. This specific feedback should be expanded on, and a change in results might appear. Hopefully, the positive effect we obtained on persuasion and perceived friendliness can be heightened by an increased contact area. The successful use of a more simple touch validated our hypotheses specifically for small areas. Thus, Peltier cells could be integrated into VR controllers as small-contact-area haptic devices, enabling their use in virtual social communication, such as virtual social media platforms. In the future, expanding the contact area and the diversity of feedback delivered will make for a sizeable goal. Thermal feedback could be rendered on a different area of the human body, such as the back or the arms.

This paper demonstrated the effect of simple haptic devices when used alone or combined. Participants chose the thermal amplitude to suit their thermal comfort, with no other change aside from warm/cool/neutral. The temperature stayed constant, and its value did not change with the agent's voice. Modifications could depend on the tone of voice or the interlocutor in dialogues. They could merely translate the audio rhythm into temperature fluctuations. These patterns could add a dimension that would give us a better comprehension of its effect. Additionally, our study focuses on the influence of thermal feedback, not vibratory ones, so we did not explore other signals, but indeed it deserves to be considered in future studies (e.g., testing signal displayed with simple LRA actuators). Different types of feedback could also be included, such as contact pressure. Its integration could increase the preexisting influences of thermal and vibrotactile feedback or add an effect on a new dimension, such as virtual presence or embodiment. Our results certainly suggest that a multimodal device could be adapted to use specific types of feedback in the appropriate context.

6 CONCLUSION

We conducted two studies evaluating the influence of thermal feedback on persuasion, co-presence, focus, thermal comfort, and perceived friendliness. Users listened to virtual agents speaking while receiving haptic feedback. The first study compared cool, neutral, and warm feedback; warmth significantly heightened the virtual agents' persuasiveness and the perceived focus of participants. The second study included warmth, vibrotactile feedback, and a combination of both. Warm + vibrations had the most positive effect on persuasion and co-presence, while warmth alone significantly increased the agents' perceived friendliness. These results suggest that some haptic feedback might be better suited for some purpose: physical warmth for social warmth, vibrations for focus and virtual presence. Combining both was effective in most contexts but not all of them, justifying the need for a modulated hybrid device for social virtual interactions.

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