Proxemic Cues for Non-Visual Perception of Virtual Humans in Mixed Reality

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Abstract

This paper discusses strategies for non-visual proxemic cues in multi-user Mixed and Virtual Reality and introduces a concept for 360-degree on-body feedback to support the localization of virtual humans. In avatar-mediated immersive environments, user representations are primarily perceived through audiovisual channels, which is misaligned with the rich multisensory interpersonal perception of real-world encounters and poses an accessibility barrier for blind and low-vision individuals. Therefore, in this work, we explore non-visual proxemic feedback and implement a multi-user Mixed Reality prototype that integrates a vibrotactile belt providing 360-degree haptic cues indicating the direction and proximity of virtual avatars. We then report insights and design considerations regarding on-body proxemic feedback derived from a hands-on expert feedback session.

Keywords

Mixed Reality, Virtual Reality, Haptic Feedback, Awareness, Proxemics, Perception

1. Introduction

In distributed multi-user Virtual and Mixed Reality (VR and MR) spaces, social interaction is predominantly mediated through embodied avatars. These environments enable us to bridge physical distances and meet, talk and move around one another in shared virtual spaces. Proxemics is an integral part of such interactions, as knowing who is nearby and where they are is essential for experiencing convincing social exchanges. In avatar-mediated environments, proxemic information is typically conveyed through visual and auditory cues, i.e., seeing each others' avatars and hearing spatially localized voice output. This setup, however, presents accessibility challenges for Blind and Low-Vision (BLV) individuals. Without vision, the simple questions "Who is here?" and "Where are they?" become difficult to answer.

In contrast to virtual encounters, real-world social exchanges are shaped by a multitude of non-visual sensory impressions. The peculiarities of people's voices (e.g., speech patterns, pitch, intonation, and loudness) alone are so rich that they inform judgments about sex, age, and personality [1], perceived social warmth [2], as well as trust and competence [3]. Body scent influences the perception of someone's gender [4] and emotional inference [5], while perceived warmth can strengthen interpersonal bonds [6] and bodily self-awareness [7]. Interpersonal affective touch supports social exchange [8] by increasing physiological synchronicity, fostering affective support and empathy [9]. Even gait patterns and vibrational footstep signatures can reveal identity [10, 11, 12]. Together, these non-visual factors contribute to how we locate and interpret other people in our social environments.

BLV individuals have to rely more heavily than sighted people on these additional sensory channels for social assessments, with hearing serving as the primary source of information [13, 14]. With all other sensory input commonly stripped away in remote avatar-mediated VR and MR, BLV users' sense of hearing is the only accessible communication channel. Using this channel to employ additional auditory cues, e.g., to support non-verbal communication [15, 16] or to indicate proxemics [17], has been shown to distract from and interfere with ongoing verbal communication [16, 17].

Thus, in this work, we investigate non-visual proxemic cues to support BLV users during social

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interactions in distributed avatar-mediated VR and MR. We discuss two strategies for delivering such feedback: environmental cues integrated into the surrounding physical space, and on-body cues delivered directly to the user's body through wearable devices. Based on this distinction, we designed concepts for providing 360-degree directional and proximity information via a vibrotactile belt, which we integrated into a multi-user MR prototype. Based on the results of a hands-on feedback session with a blind human-computer interaction expert, we gathered initial insights into the benefits and limitations of our implemented concepts and discuss design implications for future non-audiovisual social interaction in avatar-mediated immersive environments.

2. Related Work

In the following, we explore prior work that models non-visual communication channels in social MR and VR, before specifically zooming into approaches that employ such sensory cues for non-visual proxemic feedback.

2.1. Non-Visual Perception of Others in Mixed and Virtual Reality

In MR and VR, haptic sensations for interpersonal interaction have been researched in various contexts, such as the transmission of social touch [18, 19] or simulating collisions in virtual crowds [20]. These sensations are often transmitted through wearable haptic devices and usually designed to replicate real-world tactile experiences. In comparison, research on olfaction in MR and VR remains relatively scarce and rarely focused on bodily scents. However, Flavián et al. [21] found that pleasant and congruent scents promote affective and behavioral responses in VR. This suggests that incorporating bodily scents could potentially influence social exchange in VR. Kim et al. [22] found that plausible physical-virtual airflow affecting both the user and their virtual conversation partner enhances social presence in MR. This inspires speculation about whether similar effects might emerge if such airflow were caused by the movements of a virtual human, thereby conveying proxemic information. Lee et al. [23] investigated the impact of delivering vibrotactile feedback to participants' feet through vibrating floor plates, triggered by the footsteps of walking virtual humans. While participants experienced higher levels of social presence, they also exhibited greater avoidance behavior toward the virtual human. Recent work has also directly targeted BLV users' needs for multi-sensory interpersonal perception, such as Biggs et al. [15], who present non-visual design patterns for social interactions in VR, suggesting strategies on how to translate non-verbal social interactions, such as avatar appearance and body-postures, into non-visual output for BLV users. Jung et al. [16] designed audio- and haptic-driven non-verbal communication cues for BLV users in social VR, modeling signals like eye contact, head nodding, smiling, and frowning through a combination of haptic buzzing and differently pitched audio snippets. They emphasize that such cues should be unobtrusive but distinguishable during conversation. Their findings further indicate that repeated audio cues are too disruptive to the conversation, and they favor haptic cues for frequent non-verbal expressions.

2.2. Multi-Sensory Proxemic and Awareness Cues in Mixed and Virtual Reality

Few works have considered non-visual interpersonal proxemic cues for multi-user VR and MR. Ji et al. [17]'s VRBubble provides auditory cues about surrounding avatars in three concentric "bubbles" of increasing distance from the user's body: intimate, conversation, and social, providing different information depending on which bubble an avatar enters. Overall, participants found the auditory cues to be helpful, though with individual setbacks for the three tested alternatives: Discrete earcons had a steep learning curve, verbal notifications were distracting and interfered with ongoing conversations, and ambient real-world sound effects, while non-distracting and pleasant, made it hard to distinguish between individual events. Ooms et al. [24] studied the effects of thermal and haptic feedback on the perception of interpersonal distance through a heatable wristband and vibrating handheld controllers simulating a heartbeat. They did not account for the direction from which the virtual human approached.

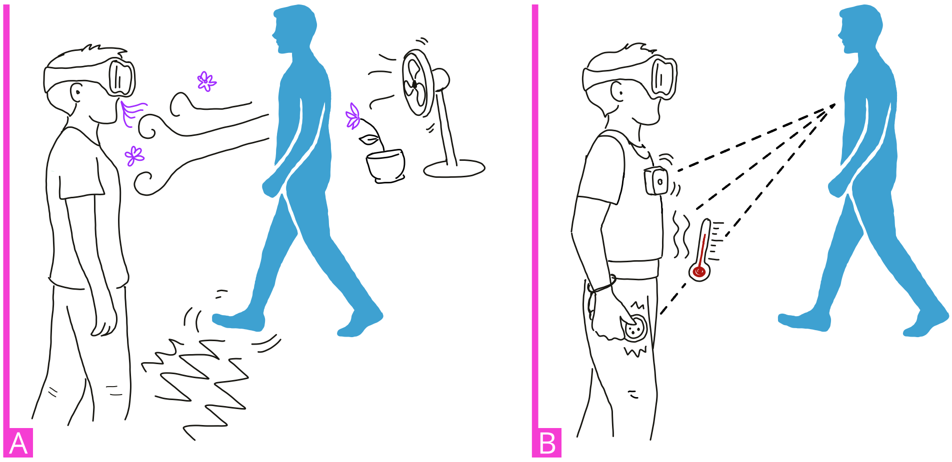


Figure 1: The two major strategies of delivering non-visual proximity cues in multi-user MR and VR: A) Environmental cues, emitted by stationary devices placed in the user's physical environment, and B) On-body cues, delivered by body-worn devices directly to the user's skin.

Results show that thermal feedback reduced perceived interpersonal distance, whereas vibrotactile heartbeat signals increased it, with the latter also increasing arousal and discomfort. These findings demonstrate that haptic and thermal cues can modulate proxemic perception. Li et al. [25] investigated vibrotactile and skin-stretch cues to support BLV users in perceiving static and dynamically moving objects in VR. They found that skin-stretch cues, where a touch probe is dragged across the back of the participant's hand, were better suited for tracking the object's location than the vibrational cues delivered at two different spots with a brief interruption. This suggests that continuous haptic motion may be beneficial for conveying spatial information.

3. Strategies for Non-Visual Interpersonal Proximity Cues in MR

The literature suggests two major strategies to provide non-visual proximity and awareness cues in multi-user MR: *environmental cues*, emitted by feedback devices positioned in the user's physical space, and *on-body cues*, delivered through wearable devices attached to the user's body. Both strategies, and their strengths, weaknesses, and suitability, are discussed in the following, and itemized in table 1 and table 2. An overview of their design dimensions is provided in the appendix (see section A.1).

3.1. Environmental Cues

Interpersonal proxemic awareness cues can be integrated into the user's physical environment by placing stationary emitting devices directly in the surrounding space (see fig. 1, A), such as fans, as employed in Kim et al. [22]'s social VR experiment, or vibrating floor plates as explored by Lee et al. [26]. Since no additional handhelds or wearables are involved, these cues may feel intuitive and closer to real-world interpersonal perception, while avoiding additional bodily load (referring to the physical and sensory burden imposed by on-body devices). They also leave the hands free, which is especially relevant for BLV users who use a white cane for navigation.

However, environmental cues may require longer familiarization periods, as the mapping between cue and meaning is often less explicit, similar to the ambient cues in Ji et al. [17]'s VRBubble project. Since possible emitting devices are largely stationary, system usage would typically be confined to a specific room or area. If multiple users share the same physical space, distributing cues in a targeted and individualized manner becomes challenging. Instead, cues are most likely perceivable by everyone in the room, unintentionally revealing social states or private interactions. Additionally, some cues quickly spread in the room without giving a clear directional indication, e.g., smell or heat, or linger afterwards, lacking a clear "off" state. Environmental cues can also interfere with each other, e.g., airflow may

Table 1
Strengths, limitations, and applicability of **environmental** non-visual proxemic cues

Strengths	Limitations
• High ecological validity / naturalness • Hands-free and low physical load • Reduced equipment complexity for the user	• High ambiguity • Limited personalization and targeting • High infrastructural overhead • Low spatial precision for certain modalities • Dependence on user position relative to the environment
Suitable for	**Unsuitable for**
• Dedicated MR rooms or labs • Shared awareness rather than individual guidance • Slow-changing or ambient proximity information • Professional, non-intimate social scenarios • Early notification rather than immediate reaction	• Highly individualized feedback • Crowded multi-user environments • Fast interpersonal interactions • Precise directional or distance encoding • Mobile or ad-hoc MR setups

disturb olfactory cues. An individual's distance from the emitting devices may also alter the perceived intensity of the cue, potentially falsifying its intended impact. Lastly, equipping a dedicated space with the necessary infrastructure can be an organizationally and monetarily costly endeavor and is most often not feasible for individual users.

3.2. On-Body Cues

Proxemic awareness cues can also be delivered directly to each individual user through wearable emitting devices (see fig. 1, B), such as haptic feedback vests [27, 28, 29], vibrating gloves [30], wearable thermal devices for the wrists, forearms, or calves [31, 32], thermal gloves [33, 34], as well as handheld vibrotactile controllers [35]. This allows personalized delivery of proxemic cues while supporting greater mobility and consistency across changing environments. Depending on where and how the devices are worn, on-body feedback can also allow for precise directional indication. On-body cues are especially suitable for time-critical and immediate information transmission, as stimulation is delivered directly to the skin or requires minimal transmission distance to reach the perceiving organ, as in the case of wearable olfactory displays [36, 37].

However, on-body cues are rather unnatural and misaligned with real-world interpersonal perception. They also add to the bodily load, as wearable devices can be restricting or uncomfortable. Such devices need to be individually fitted and customized, as they can be difficult to apply and might accommodate all body sizes equally well. Furthermore, personal boundaries regarding stimulated body areas, as well as tolerance for intensity and duration, vary between individuals. Also, importantly, depending on the form factor, on-body devices may occupy the user's hands, interfering with the usage of a white cane.

As we set out to explore individualized support to improve accessibility in common multi-user VR and MR environments for BLV users, we consider on-body cues to be the most suitable to our intended use case, despite the limitations. Therefore, we focus on an on-body setup for our concepts, which we will expand upon in the following chapter.

4. A Concept for On-Body Interpersonal Proxemic Cues

To explore non-visual interpersonal proxemic cues for BLV users in multi-user MR, we designed strategies for haptic feedback delivered through a vibrotactile belt.

Table 2
Strengths, limitations, and applicability of **on-body** non-visual proxemic cues

Strengths	Limitations
• High individualization and precise targeting • High spatial and directional precision • Consistency across environments • Effective for time-critical interactions • Movement flexibility	• Lower ecological plausibility • Increased bodily load and discomfort • Hands and body parts may be occupied • Equipment complexity for user • Social visibility and stigma
Suitable for	**Unsuitable for**
• Individualized proxemic feedback • Precise directional and distance cues • Crowded multi-user environments • Mobile or ad-hoc MR setups • Safety-critical interactions • Users who benefit from strong, reliable cues	• Scenarios prioritizing realism or social subtlety • Long-duration sessions with continuous feedback • Users sensitive to touch or vibration • Contexts where body must remain unencumbered

4.1. 360-Degree Proximity Cues Through a Vibrotactile Belt

The belt provides 360-degree feedback across eight equally sized zones around the wearer's hips (see fig. 2), enabling rapid detection of approaches from any direction. These feedback zones are mapped to the user's environment. If another user's avatar enters one of the corresponding spatial sectors, vibration is activated in the respective belt segment, allowing for directional estimation of the other person's position. The vibration intensity is mapped to the approaching user's proximity: the closer they are, the stronger the vibration. An additional short audio cue is activated and combined with a light vibration when virtual users enter or leave the shared virtual space, with a slight distinction between the cues for both actions. Apart from this short notification, the audio channel is exclusively reserved for verbal communication.

4.2. Implementation

We implemented our prototype for the Meta Quest 3[1] in combination with the feelSpace naviBelt[2], a vibrotactile belt specifically designed to support BLV individuals during navigation. The prototype was implemented using Unity 6[3], the Meta SDK[4], a custom Python program for the belt control, and a separate locally hosted Python-based webserver to facilitate communication between the head-mounted display (HMD) and the belt.

In the multi-user MR application, two users connect to a shared virtual space from different physical locations and are represented as Meta avatars in each other's environments. The user equipped with the vibrotactile belt (hereafter belt user) then receives the initial auditory and vibrational awareness cues when the other user (hereafter non-belt user) joins the session. Both users can communicate with each other via spatial audio voice chat. The non-belt user's position and proximity to the belt user are continuously tracked and translated into vibrotactile feedback for the belt user. The belt user is equipped with handheld controllers to manually stop the vibration if needed (see fig. 2, B).

4.3. Evaluation

We designed and conducted a pilot study with an invited expert to gather initial feedback on our concept. The expert is a fully blind individual with several years of professional experience in the

[1]https://www.meta.com/quest/quest-3/, last accessed 16.02.2026
[2]https://feelspace.de/en/, last accessed 16.02.2026
[3]https://unity.com/, last accessed 16.02.2026
[4]https://developers.meta.com/horizon/downloads/package/meta-xr-sdk-all-in-one-upm/, last accessed 16.02.2026

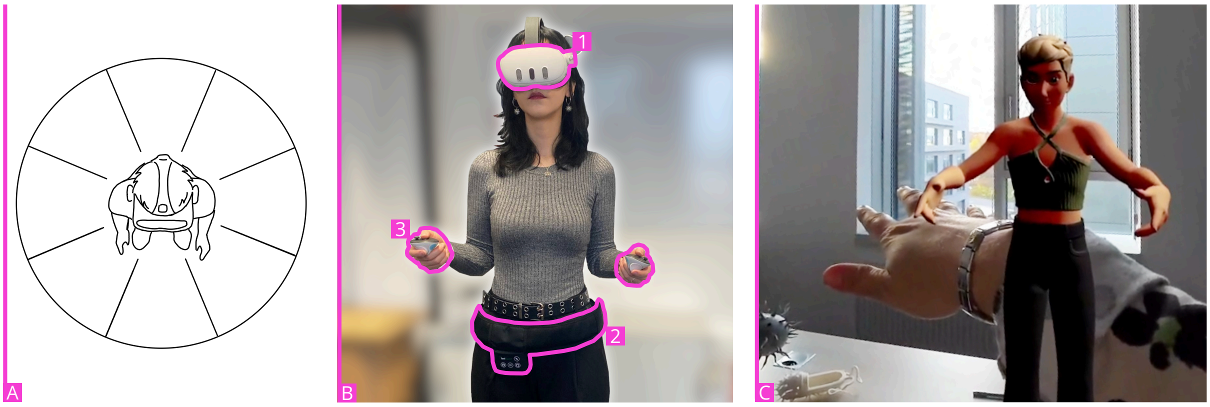


Figure 2: In our prototypical implementation, on-body cues are spread over A) 8 vibration zones around the body, by combining a B.1) head-mounted display with a B.2) vibrotactile belt, and B.3) controller input to regulate the vibration. Combining spatial audio with directional vibrations enables users to C) approximate the position of a virtual avatar, here shown by pointing in the avatar's general direction.

field of human-computer-interaction in the context of disability services, qualifying them to provide feedback from both a system design and end-user perspective.

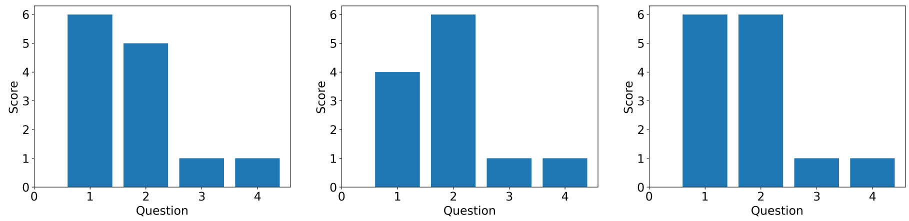
4.3.1. Process

Upon arrival, the participant completed a demographic survey and signed a privacy consent form, before then being introduced to the purpose and procedure of the experiment, as well as the devices involved. The participant was equipped with the HMD, the vibrotactile belt, and two controllers, and received instructions on how to stop the vibration if discomfort arises. We studied two conditions, vibration only (V) and vibration and audio (VA), against a baseline where only spatial audio (A) was provided. During each condition, a virtual avatar walked around the participant for a couple of seconds before coming to a halt. In both the A and VA conditions, a spatial audio clip with a casual monologue was played during the avatar's movement, with its sound source attached to the avatar's dynamic position. In both the V and VA conditions, the participant received directional and proximity cues through the vibrating belt. After the avatar stopped, both audio and vibration were deactivated. The participant was then asked to point toward the perceived final position of the virtual avatar and to indicate whether they believed the avatar to be close or farther away. After each condition, the participant also rated their perceived social presence. Following the experiment, a semi-structured interview was conducted, inquiring about the participant's impressions, feedback and suggestions in regards to the presented concept.

4.3.2. Measurements

During the experiment, we recorded the participant's ability to correctly identify the avatar's direction and its perceived proximity to the participant. To gain insight into potential changes in social presence, we administered the self-perception items from the co-presence subscale of Networked Minds Social Presence Inventory [38] (see section A.1). Our concluding semi-structured interview was guided by the following questions:

- Was the vibration helpful? If so, in what way?
- How useful do you consider the vibrotactile feedback as a standalone modality, without audio?
- How useful do you consider the vibrotactile feedback in combination with audio?
- What would you change about the vibrotactile feedback?
- Are there situations in which you would prefer a specific modality, or no modality at all?
- Which other modalities could you imagine for conveying interpersonal proximity indications?



(a) Audio only (b) Vibration only (c) Vibration and audio

Figure 3: Results of the the self-perception questions of the co-presence area of the NMSPI

4.3.3. Results

Across conditions, we observed no substantial differences in the participant's ability to point out the avatar's direction. In both the A and VA conditions, the avatar's position was identified quickly and correctly. There was a very slight discrepancy between the participant's perception of the avatars position and its actual position in the V condition, which may be due to the granularity of the belt's vibration zones (see fig. 2, C). While the belt provides directional feedback within 45-degree segments, the absence of audio cues limits further refinement. The participant struggled to reliably judge the avatar's proximity in all conditions. The answers to the NMSP questions varied only slightly across conditions, with high scores for questions 1 and 2, which relate to the feeling of sharing a space with a partner, and low scores for questions 3 and 4, which relate to feeling disconnected from and unaware of the partner (see section 4.3.3). VA achieved the highest scores for questions 1 and 2.

In the interview, the vibration was deemed to be generally helpful. While audio alone was already largely sufficient, the combined condition was perceived as the most helpful, because it underscored the auditory perception and helped with correctly localizing the avatar behind the participant's back, as this was perceived to be difficult based on audio only. However, the participant did not notice the changes in vibration intensity, and therefore deemed it useless for judging proximity. When asked about suggestions to change or improve the feedback, they suggested vibration patterns instead of intensity to model changes in proximity, e.g., by increasing the speed of a pattern when someone comes closer. The continuous vibration was also perceived to be annoying, and the participant suggested a "vibration on-demand" feature instead, allowing users to actively query the position of others instead of passively receiving constant feedback. Alternatively, they suggested triggering vibration only when position changes exceed a defined threshold.

The participant also mentioned that the belt's placement could be sensitive and uncomfortable for some users, but agreed that it is the most suitable for 360-degree feedback. They further said that, in a one-on-one conversation, they don't necessarily need to know where their conversation partner is at all times. In a casual conversation, they would prefer to solely have spatial audio because it feels the most natural. Though, during longer stretches of silence, they would like to have occasional vibrational feedback to confirm the other person's presence. Finally, the participant emphasized that the greatest potential of the system lies in multi-user scenarios, where it could help to distinguish the amount and direction of multiple people. They did not have any further suggestion for alternative modalities to indicate interpersonal proximity, but expressed a strong aversion to thermal feedback, describing it as overly intrusive.

5. Discussion

Through our evaluation, we gained valuable initial insights and impulses for further discussion and future work. Since we only performed our experiment with one participant, there is no statistical significance to the results and any outcome can only be interpreted as the personal experience of an individual. Yet, some discussion points arise. Although the participant considered the combined condition (vibration and audio) to be the most helpful, they also suggested that spatial audio alone was sufficient to locate the user in a casual conversation. They would appreciate vibrational feedback mostly to confirm the other user's position during longer stretches of silence in a conversation. Continuous vibration, however, was perceived as annoying over time. This aligns with prior research where vibrotactile cues increased perceived interpersonal distance, arousal and discomfort [24], as well as avoidance behavior [23] toward virtual humans. During real-world encounters, when conversational silence arises, BLV individuals still perceive environmental changes through their additional senses. In remote MR, these sensory channels are unavailable. This, and the expressed wish for an "on-demand" feedback system, bring up a potential design consideration: As auditory cues remain the primary communication and perceptional channel [13, 39], further feedback should likely function as subtle reinforcements, or as a fallback when it fails to deliver the necessary information, e.g., during conversation gaps or when the audio source is difficult to locate. So, in conclusion, while vibrotactile cues have the potential to support interpersonal perception of virtual humans, they should likely be employed sparingly and only when necessary, or only on demand.

Device placement emerged as another relevant consideration. Perceived intimacy and intrusiveness of on-body feedback vary substantially across individuals. While the torso lends itself to the employment of wrap-around devices for 360-degree perception, areas on the limbs, such as forearms or calves, might be better suited as they potentially feel less intimate. Here, the degrees of freedom of the limb's movements need to be taken into account, as well as asymmetry if only applied to one of a pair. A promising endeavor could be the development of a feedback device of which the emitting parts can be decoupled and placed flexibly around the body, suiting individual user's preferences.

The mapping between cues and vibration properties is another important consideration. In our experiment, the participant did not notice changes in vibration intensity, and therefore proximity. Here, it is likely that the difference in intensity was not big enough, as we did not exhaust its potential out of concern for discomfort. However, if potential discomfort should be accounted for, increasing the intensity of the stimulation is not a reasonable alternative. It is also possible that the intensity has been dampened by multiple layers of clothing between the belt and the skin. Yet, again, simply placing it closer to the skin or onto more sensitive areas is not a feasible consideration. Instead, we believe that vibration intensity is not suitable to model specific awareness cues. Instead, more easily discernible and less intrusive sensations should be employed, such as vibration patterns, as suggested by the participant.

6. Conclusion

We investigated non-visual interpersonal proxemic cues for avatar-mediated multi-user Mixed and Virtual Reality (MR and VR) to support blind and low-vision (BLV) users. We discussed environmental and on-body cues as two alternative strategies and implemented an on-body prototype that integrates an MR head-mounted display and a vibrotactile belt providing 360-degree feedback across eight discrete zones. In our implementation, we modeled directional indications through zone selection and proximity through vibration intensity. Initial feedback was gathered in a hands-on session with a blind human-computer interaction expert. From this, we conclude that haptic interpersonal proxemic cues have the potential to enhance the perception of virtual humans in multi-user MR, but should not be employed as replacements for auditory spatial information, but rather as contextual supplements. Continuous haptic feedback may increase discomfort and may alter the mood of the social interaction. Instead, adaptive or on-demand systems, activating during conversational gaps or manually triggered during moments of uncertainty, may better align with user needs.

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Declaration on Generative AI

The authors have not used any Generative AI tools.

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A. Appendix

A.1. Dimensions of Environmental and On-Body Feedback Cues

Table 3
Comparison of environmental and body-based non-visual proxemic cues in multi-user MR

Dimension	Environmental Cues	Body-based Cues
Reference Frame	Allocentric	Egocentric
Coupling to User Pose	Independent of user pose	Strongly coupled to orientation
Personalization	Low	High
Targeting Precision	Global or group-level	Individual
Directional Fidelity	Coarse to moderate	Moderate to high
Temporal Resolution	Low to moderate (often ambient)	High (event- and time-critical)
Ecological Plausibility	Moderate to high	Low to moderate (often symbolic)
Bodily Load	None	Low to high (depending on device)
Hands-Free Interaction	Fully hands-free	Potential interference
Scalability (Multi-user)	Limited	High
Infrastructure Requirements	High, room-specific	Low to moderate, portable
Flexibility Across Spaces	Low	High
Suitability for BLV Users	Good for ambient awareness	Good for precise proxemics
Social Acceptability	Rather high, subtle	Varies, may be visible
Typical Modalities	Audio, airflow, vibration, smell	Vibrotactile, thermal, on-body audio
Typical Use Cases	Ambient presence, shared awareness	Direction, distance, approach detection

A.2. Networked Minds Social Presence Inventory Questions

The specific questions of the NMSPI [38] asked in our experiment. The participant was asked to rank them on a scale of 1 and 7, with 1 being "I do not agree at all" and 7 being "I completely agree".

1. I often felt as if my partner and I were in the same room together.
2. I was often aware of my partner in the room.
3. I hardly noticed my partner in the room.
4. I often felt as if we were in different places rather than together in the same room.