Bridging Realities in a Heartbeat –
How Integrating Heartbeat Signals Supports Collaboration in Mixed Reality

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Fig. 1. It has been found that heartbeat-related stimuli are visually processed and have relevance for social interactions in real life. However, such physiological signals are rarely represented in virtual environments. In our work, we propose to virtually mimick and enhance heartbeat signals to enrich embodied interactions across the MR continuum, bridging real and virtual collaboration.

Mixed Reality (MR) has great potential for remote collaboration, as remote users can be integrated with co-located users while facilitating similar richness in verbal and nonverbal communication, comprising gestures, facial expressions, voice, and body posture. However, current approaches mostly neglect more subtle cues, like physiological signals, which have been shown to be relevant during social interactions. We propose that physiological signals, such as heartbeats, should be integrated into virtual user representations to facilitate more effective remote collaboration in MR. In this work, we discuss the integration of heartbeats specifically, to enrich embodied interactions across the MR continuum, further bridging the gap between co-located and remote collaboration in MR. In addition, we identify key challenges and propose future research directions to support this vision.

CCS Concepts: • **Human-centered computing → Virtual reality**; **Mixed / augmented reality**; • **Information systems → Collaborative and social computing systems and tools**.

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1 Introduction

Mixed reality (MR) [13, 18] has great potential as a communication medium [16] that can enrich remote collaboration with qualities typically known from co-located collaboration (e.g., nonverbal communication) [5]. MR can create the illusion that remote users are *virtually co-located* by integrating them in the physical environment of a local user (e.g., as 3D avatars) [4, 5, 11]. With their abundance of cameras and sensors, current off-the-shelf MR devices allow detailed tracking of the body (e.g., posture, gestures, facial expressions, or gaze) that can be mapped to user representations [17] (e.g., virtual avatars) in real-time. With this, user behavior and nonverbal communication become plausible–eventually leading to a sense of social presence [19]. In general, the presentation of nonverbal communication cues mainly focuses on external aspects of the body, such as facial expressions, gestures, body postures and movements, or nonverbal vocalizations [9]. However, recent research has emphasized the importance of other bodily cues—i.e., internal body signals—for social interaction [1]. These signals, such as variations in heartbeats from which heart rate variability (HRV) is derived, have the potential to synchronize between different individuals in different contexts, leading to a phenomenon known as physiological synchronization. Such synchronization has been established to be beneficial for leisure [3] and professional activities [7] as well as to have an influence on empathy [15]. Interestingly, humans are able to perceive and process internal body signals of others even virtually (e.g., from a video) [6]. Therefore, we argue that for *designing successful remote collaboration using MR*, internal body signals should be integrated as part of virtual user representations. This is relevant across the entire MR continuum, as increasing virtuality reduces the perceptability of real-world physiological signals—hypothetically increasing the potential (and need) for augmenting user representations with physiological signals (see Figure 1). However, this augmentation of user representations is not straightforward, with challenges ranging from the technical aspects, such as the real-time capture and transmission of these signals, to the design of the visualizations and integration with the user representation. Therefore, in the scope of this paper, we discuss how to integrate real-time physiological signals (i.e., using the example of heartbeat signals). Additionally, we propose ways to represent the heartbeat across the MR continuum and diverse distributed teams.

2 Prerequisites for Integrating Heartbeat Signals into User Representations in MR

To integrate heartbeat signals into user representations, the respective physiological signals need to be tracked, processed and presented in real-time. Nowadays, widely used wearable sensors, such as smartwatches, offer a non-intrusive way to track physiological data. However, this sensor data may lack the information needed to realistically represent internal body cues and replicate effects observed in real-world human interactions. For example, when tracking heartbeat signals, smartwatches relying on optical heart rate sensors (photoplethysmography) can measure the current heart rate but lack the temporal resolution to capture details, such as exact variations in heartbeat timings to accurately determine HRV. Other devices, such as the Polar H10[1] chest-strap that incorporates a heart-rate sensor using a 2-channel electrocardiogram (ECG) with a sampling rate of 1000 Hz, do allow continuous real-time recording of heart rate signals

[1] https://www.polar.com/us-en/sensors/h10-heart-rate-sensor – last accessed: 7th March 2025

with high precision, but in comparison to the smartwatch they lack the comfortable wearability for all-day use. As a consequence, it is important to investigate whether heart rate alone (captured with a smartwatch) is sufficient to effectively mimick signals that elicit similar effects as observed in real-world social interactions, or whether we need ECG-grade heartbeat details (e.g., from the Polar H10).

Independent of sensor technology, the tracked physiological signals must be processed, transmitted, and visualized on the remote collaborators' devices, which introduces latency. Since sensors themselves often lack direct network communication, the data is typically first transmitted to an intermediary device, such as a smartphone (e.g., via Bluetooth) before processing, causing additional delay. Integrating the sensors for physiological signals into HMDs could reduce latency at this step. Then, the raw data must be processed either locally or remotely to extract the necessary information for accurate representation of internal body cues, which can introduce further (significant) latency. For example, for cardiac cues important information might include the timing of heartbeats (e.g., the R-peaks), as well as the variability of the time interval between two heartbeats, commonly referred to as HRV. The standard algorithm to detect R-peaks in ECG signals is the Pan-Tomkins algorithm [14], which introduces a delay of 270 ms for a signal sampled at 200 Hz. Here, novel processing methods are needed to balance accuracy and latency for real-time heartbeat representation effectively. In summary, on the technical side, we have to overcome the following challenges:

- ensuring continuous and robust access to physiological signals, such as heartbeats;
- determining which details of physiological signals, i.e., heartbeats, are needed to effectively integrate these in user representations;
- reducing the latency of signal processing and transmission; and
- optimizing current signal detection algorithms for real-time representation.

3 Representing Heartbeat Signals across the MR Continuum

Besides tracking and processing, we face the challenge of how to represent heartbeat signals in MR effectively. Importantly, we must consider which representation is most suitable for different facets of the MR continuum, as this may vary with the degree of virtuality of the user and environment. Furthermore, we need to consider how we can effectively apply these signals for social interactions in larger groups without, for example, overwhelming or distracting users with the multitude of animations. Consequently, an essential question is: what are suitable representations of heartbeat signals in MR?

In literature and consumer products, a diverse range ideas has been presented, yet, these differ in purpose. The most familiar visual representation is a heart-shape that is animated to increase in size as if beating, as known from the Apple Heart Rate app[2], pop culture references (e.g., heart emoji), and related work (e.g., [8, 10]). Further, a yellow body outline that flashes in synchrony with the heartbeat [2] and skin color change [12, 20] have been used in research; the latter is based on the actual physiological change in our bodies during each heartbeat. For settings such as remote collaboration in larger teams, we speculate that coarse approaches like the yellow outline from Aspell et al. [2] may be perceived as intrusive and distracting. Instead, a smaller visualization, such as an animated heart on the chest could be beneficial, which can also reduce visual clutter in group scenarios, as it is only visible when facing the respective user.

Yet, compared to real-world signals such visualizations are of course unnaturally explicit and obvious. Hence, in hybrid settings, where some collaborators are co-located, and some are remote, we might subconsciously perceive physiological cues from our co-located collaborators, while physiological cues on the avatars would be overly explicit.

[2]https://apps.apple.com/us/app/heart-rate/id1584215812, last accessed: 7th March 2025

To achieve comparable expressiveness and recognizability of the heartbeat cues across all users, we could additionally augment the physically co-located collaborators with explicit visualizations, e.g., by overlaying them or adding a physical display (cf. Figure 1). Another approach could be to implement subtle changes in skin color on the avatars, making the signal less obvious or even displaying it below the threshold of conscious perceptibility. This could mimic the actual change induced in human skin by each heartbeat and, therefore, may not require the augmentation of physically co-located collaborators. Additionally, if changes occurred below the threshold of conscious perception, we would avoid the problem of distraction that may result from having multiple people with flashing animations in a group setting. Of course, the hardware must be able to present such subtle changes, and we need all thresholds for different skin shades to be fully inclusive. Also, as the underlying mechanics of how we perceive such cues are currently unclear, it is critical to establish interdisciplinary approaches in order to integrate the right signals and enable physiological synchronization within groups. To summarize, the representation of heartbeat signals integrated in user representations requires researchers to find answers to the following open questions:

- What representations of heartbeat signals are suitable and work for diverse distributed MR systems?
- Which representation is most effective for creating physiological synchrony of heartbeat signals for different manifestations on the MR continuum?
- How can we represent heartbeat signals in larger user groups without generating unwanted distractions and visual clutter?

4 Conclusion

Mixed Reality holds great potential for remote collaboration, as remote users can be integrated with co-located users with similar richness for verbal and nonverbal communication. Yet, despite research showing that internal physiological signals, such as heartbeats, influence group behavior and dynamics, integration into MR settings is currently largely missing. We argue that such an integration is needed to create a richer, more realistic, and thereby more effective collaboration. Virtually representing these physiological signals brings some new challenges and open questions, which we identified based on our experience with designing such systems and related work. Among these questions are: What signals and which signal quality do we need? Are heart rate data from smartwatches enough, or do we need more elaborate sensors that provide true ECG signals? In this context, we discussed that real-time tracking, processing, and transmission of heartbeat data remains a challenge, as all steps involved introduce latency. Additionally, from existing literature, it is unclear how these signals should be represented, as adding blinking visualizations to each avatar might lead to significant visual clutter in larger group settings. Finally, with very explicit visualizations on remote collaborators, we need to enhance the natural signals of co-located collaborators to harmonize both groups.

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