Comparing Physiological Synchrony and User Copresent Experience: A Quantitative-Qualitative Gap

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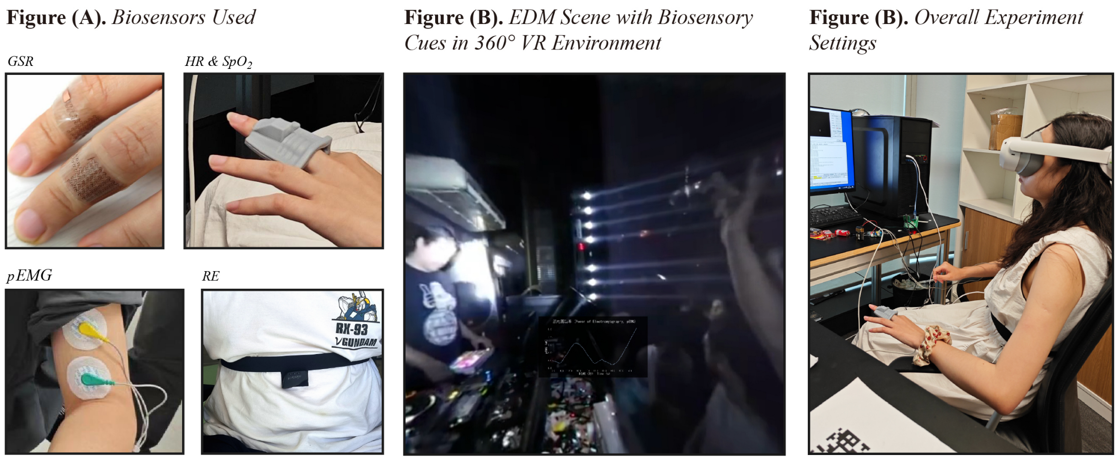

Fig. 1. (A) Biosensors Used, (B) EDM Scene with Biosensory Cues in 360° VR Environment, (C) Overall Experiment Settings

As technology-mediated social interaction in virtual environments prevails, recent HCI studies suggested incorporating biosensory cues that reveal users' inner states to facilitate social information sharing and augment copresent experience. Physiological synchrony is believed to be engaged in several important processes of copresent experience. However, what impact different biosensory cues have on physiological synchrony and users' copresent experience remains yet underinvestigated. This study selected virtual reality (VR) electronic dance music setting and integrates five different bio-signals, namely power of electromyography (pEMG), galvanic skin response (GSR), heart rate (HR), respiration effort (RE), oxyhemoglobin saturation by pulse oximetry (SpO_2). A non-randomized controlled experiment with 72 valid participants revealed that GSR enhanced physiological synchrony significantly. However, semi-structure interviews with 10 participants indicated that RE and HR provided the strongest user-perceived copresent experience, which implies an intriguing quantitative-qualitative gap. Five design implications were further synergized for future copresent experience design based on biosensory cues.

CCS Concepts: • **Human-centered computing** → **Social content sharing**; **Empirical studies in collaborative and social computing**; *Laboratory experiments*; *Empirical studies in HCI*.

Additional Key Words and Phrases: Physiological Synchrony, Copresent experience, Biosensory Cues, Virtual Reality

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1 Introduction

The COVID-19 pandemic has accelerated the prevalence of technology-mediated social interactions across work, education, and entertainment domains [51, 52]. Large-scale virtual and hybrid events have become commonplace, e.g. the social VR platforms *AltspaceVR*, *RecRoom* and *VRchat* [13], the *COLDPLAY VR concert* [3], and the *Online IEEE VR Conference 2021* [34] etc. As supportive technology, VR allows for hyper-spatiotemporal and multi-sensory communication, thus resulting in higher social presence, motivation and enjoyment [36, 52]. However, current avatar-based social paradigms face potential risks such as the uncanny valley effect [22, 45], stereotyping [16], and various forms of social abuse [20, 33, 52]. To this end, the HCI research community has proposed alternative paradigms and solutions by incorporating biosensory cues that reveal users' inner states [16, 32]. These cues, derived from physiological data, are transformed into user-perceived social information, potentially enhancing interpersonal communication and interoceptive awareness [26, 27, 32].

Physiological synchrony, defined as the co-occurrence and interdependence of physiological activity between individuals, encompassing the association of their behavioral, physiological and emotional activities over time, has emerged as a crucial factor in technology-mediated social experiences [2, 8]. This phenomenon can result from the primitive process that relies on the mirror-neuron system to mimic the physiological states of others [15, 26]. It serves as a physiological indicator of copresent experience, empathy, and sympathy [15, 16, 44]. However, most current HCI research relies solely on subjective evaluations, lacking comparative studies that explore the relationship between objective physiological synchrony and subjective copresent experiences [16, 32, 41, 44].

This study aims at acquiring empirical knowledge and preliminary insight for leveraging multi-source biosensory information as alternative social cues to enhance technology-mediated copresent experience. We grounded on and extended existing research [16, 32] by collecting multiple types of factual biosensory data and comparing their effects on users' objective physiological synchrony and subjective copresent experience. Specifically, we selected the VR electronic dance music (EDM) scenario and conducted a non-randomized controlled experiment with semi-structured interviews to obtain users' objective data and subjective feedback of biosensory information in enhancing copresent experience. Explicitly, we intended to answer the following two research questions (RQs): First, can physiological synchrony be enhanced by presenting another person's bio-signals, i.e. pEMG, GSR, HR, RE, SpO_2? (**RQ1**) And if yes, Can enhanced physiological synchrony affect subjective user experience, i.e. user-perceived copresent experience, user-perceived empathy? (**RQ2**) The overall research structure and flow were shown in Figure 2.

By addressing the two RQs above, our contributions are two-fold:

- We collected and compared five different biosensory cues (pEMG, GSR, HR, RE, SpO_2) and their respective effects on users' copresent experience in virtual environment, all based on real bio-data.
- We combined both quantitative measurement of physiological synchrony and qualitative evaluation of user experience to form a more comprehensive understanding for utilizing biosensory cues, resulting in five design implications.

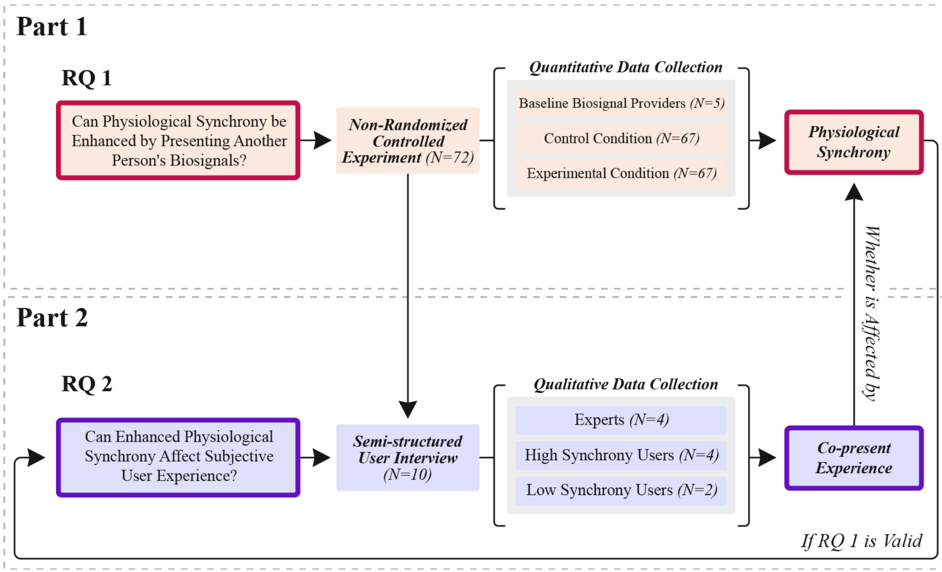

Fig. 2. Research Framework and Flow.

2 Background

Copresent experience, the perceived sense of sharing an environment with others, is crucial in VR social interactions [14, 31]. This foundation for various positive social outcomes, including empathy formation, has been extensively studied [7, 18, 24, 37, 39]. For instance, it underlies empathy formation, enabling individuals to understand and respond to others' emotional states and intentions [18, 24].

In virtual environments, users interact through digital avatars that replicate **explicit social cues** like facial expressions, postures and gestures to enhance the perceived richness of the medium [21]. While high-precision animation enhances visual realism and improves cognitive-behavioral reactions [4, 25, 42, 49], the impact of avatars on copresent experience remains debated. Hyper-realism may evoke aversive responses, potentially hindering accurate social judgments [22, 45]. Compared to the explicit social cues, **implicit social cues** that reveal and reflect individuals' internal psychophysiological states offer an alternative paradigm for technology-mediated social interaction and information sharing [35]. As one source of implicit cues, biosensory information has the potential to enhance interpersonal communication and interoceptive awareness [27, 32]. This approach can mitigate biases related to race, gender, and class, potentially safeguarding social norms and equality [16, 51].

Although fundamental to the study of social behavior, assessing copresent experiences affected by biosensory cues is challenged by the difficulty of quantification [10]. One of the main approaches is synchrony measurement, which has been proposed as a robust assessment of social connectedness and copresent experience in digital interactions. Generally, the information carried by physiological signals originates from autonomic responses—the autonomic nervous system (ANS) controls bodily functions to enable reactions to external stimuli [10]. Therefore, physiological synchrony can be calculated by analyzing the physiological signals between interacting individuals.

Current research identifies five major bio-signals capable of representing physiological synchrony involved in social interaction. HR, a reliable indicator of ANS activity, has been shown to reflect stress and emotional fluctuations during interactions, with studies demonstrating significant associations between HR synchrony and perceived social presence in mediated communication [15, 44]. GSR, measuring skin conductance, provides insights into emotional arousal and intensity of interactions, with higher GSR synchrony observed in emotionally charged shared experiences [44]. RE offers data on relaxation or tension levels, with research indicating higher RE synchrony in cooperative tasks, suggesting its role as a proxy for shared emotional and cognitive states [28]. SpO_2 has been utilized to gauge physiological engagement, with studies in virtual reality settings showing associations between SpO_2 synchrony and elevated levels of copresent experience, particularly in activities demanding high concentration and interaction [26]. Lastly, pEMG captures muscle activity, especially facial expressions, with research in dyadic gaming and virtual environments demonstrating correlations between pEMG synchrony and perceived emotional alignment [29]. Collectively, these findings suggest that physiological synchrony, as measured through the alignment of these various bio-signals, serves as a potent indicator of copresent experience that can be used to detect the influence of biosensory cues.

3 User Experiment

3.1 Overall Design

This research received approval from the Ethical Review Board of the corresponding authors' institution. Before the experiment, a participant would be provided a detailed account of the experiment purpose, the use of collected bio-data and other privacy and security related explaination. Then we asked the participant to sign a informed consent form. Compensation was offered upon experiment completion, and participants could withdraw anytime during the experiment.

The experiment was conducted in a laboratory environment as shown in Figure 1C. Each participant was equipped with sensors and briefed on the EDM experience. We chose EDM as the focus for copresent activities. Compared to a range of calming activities such as meditation or meetings, EDM provides greater sensory stimulation that can more immediately and rapidly evoke significant emotional changes in participants. This allows us to more effectively assess physiological synchrony of each biological channels. Meanwhile, watching EDM video clips in a seated position allows for exploration without excessive movement, thereby minimizing motion effects on biosensory data capture. Participants were informed that they would experience EDM with other users. They faced two conditions: an experimental condition with biosensory cues and a control condition without. We counter-balanced the conditions to eliminate possible bias due to the experimental sequence.

3.2 EDM Setting in VR Environment

Fig. 3. Virtual Environment. (A) Fixation Cross, (B) Control Condition - without Biosensory Cues, (C)Experimental Condition - with Biosensory Cues (GSR Signal as Example). Note: The Figure has been Cropped for Readability.

We developed a two-part video scenario: a resting state induction followed by an EDM experience. The resting state used the Eyes On a Crosshair (EO-F) method to standardize participants' attention and emotions [40, 47]. A 50-second animation featured a central black cross simulating breathing before fading (Figure 3A). The EDM experience used a 300-second clip from a public Youtube channel[1]. This placed participants in a dark nightclub, facing the DJ amidst a lively crowd (Figure 3B). We combined these using Adobe Premiere, creating a 6:50-minute video embedded into VR via the PICO Developer platform.

We leveraged pre-recorded real human bio-signals as biosensory cues, simulating another user's presence to derive credible physiological synchrony. Prior to the main experiment sessions, raw data was collected from five baseline providers (3 males, 2 females, all 21 years old) experiencing the same VR EDM scene to form the basic cues. We selected the data with the most significant amplitude changes that is relatively more perceivable for the participants, and segmented them into 60-second intervals, which were then aggregated to form one complete bio-signal dataset encompassing all five measured channels.

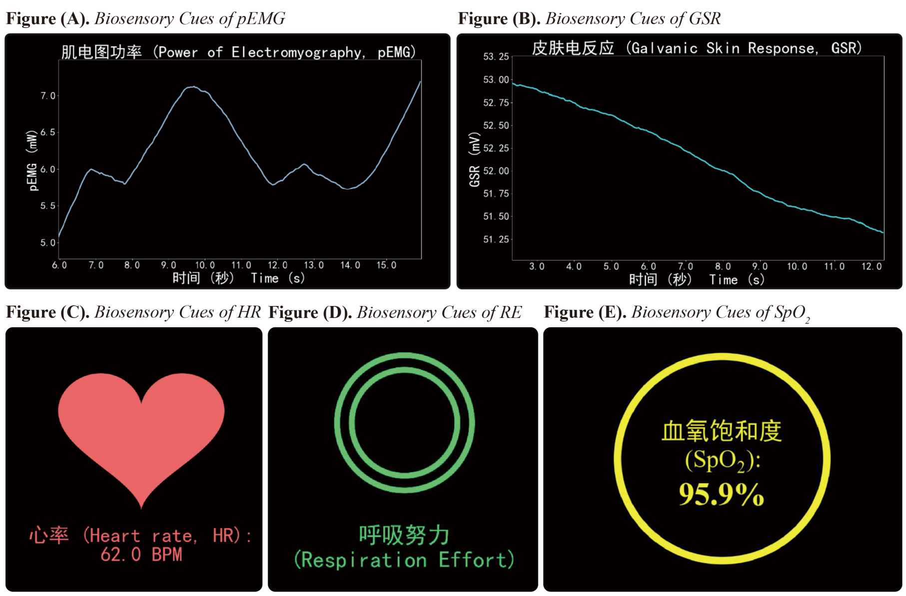

Fig. 4. Biosensory Cues. (A) Power of Electromyography, pEMG. (B) Galvanic Skin Response, GSR. (C) Heart Rate, HR. (D) Respiration Effort, RE. (E) SpO_2

As shown in Figure 4, we intentionally presented the biosensory cues as basic chart-based visualizations, so as to reduce the bias caused by extra visual representation of the bio-signals, thereby standardizing physiological measurements. pEMG and GSR were shown as line graphs, HR as a beating heart symbol, RE as concentric circles, and SpO_2 as a ring. Cues were displayed sequentially for 60 seconds each in the order: RE, pEMG, GSR, HR, and SpO_2. Labels in English and Chinese with 85% transparency enhanced comprehension without obstructing the view. In the experimental condition, cues appeared at the lower middle of the VR EDM view (Figure 3C), while the control condition had no cues (Figure 3B).

[1] https://www.youtube.com/watch?v=DbUrKkb4JJ4 Abel Meyer's 360-degree VR performance at Minimal Attack in Buenos Aires

Before the experiment, operators informed participants that the bio-signals in the experimental condition represented real-time physiological data from another user experience the same VR EDM with them.

3.3 Biosensory Data Collection and Analysis

From 76 participants who took part in the main experiment sessions, we collected valid data from 67 subjects (9 were excluded due to inaccurate). The validated participants, aged from 8 to 60 (mean = 25.09, SD = 9.82), with an almost equal gender distribution: 33 males (49.25%), 33 females (49.25%), and one identifying as other (1.49%). Their educational backgrounds were also varied: 8 had primary school education (11.94%), 2 secondary school (2.99%), 28 undergraduate or associate degrees (40.5%), and 29 master's degrees or higher (43.2%). We tried to include as diverse a range of participants as possible, as individual differences like age, education, cognitive abilities should not be ignored either. Regarding VR experience, 24 had no prior experience (35.82%), 36 had very limited use (53.73%), 6 used VR occasionally (8.96%), and 1 participant, a professional VR developer, used VR frequently (1.49%).

Our experiment used four non-invasive surface physiological sensors to collect participants' bio-signals during the VR EDM experience. The equipment included a strap-on respiration sensor (ElasTech), dual-channel pEMG sensor module kit (Sichiray), GSR module kit (Sichiray), and fingertip digital SpO_2 and HR detection module (Tonglian Chuangke), all modified for optimal performance. As shown in Figure 1A, GSR data were collected from the right index and middle fingers, pEMG from the right biceps brachii, HR and SpO_2 from the left fingertip, and Resp data from a sensor between the chest and abdomen. The overall setup was shown in Figure 1C.

To evaluate the effect of biosensory cues on physiological synchronization, we computed correlations between participants' physiological signals and baseline signals, analyzing for significant increases with cues present. Given potential time lags in physiological responses and their possible variations over time, we employed the Weighted Cross-Correlation (WCC) analysis method [11]. This approach provides a more nuanced analysis compared to traditional correlation coefficients or cross-correlation over entire signal segments.

The fundamental principle of WCC involves segmenting two signals, $\boldsymbol{X}\ \{x_1, x_2, \ldots, x_N\}$ and $\boldsymbol{Y}\ \{y_1, y_2, \ldots, y_N\}$, both of length N and sampled at intervals of s, into overlapping sub-windows, each of length w_{max} and with a time interval of s. These sub-windows, denoted as $\boldsymbol{Wx}^k$ and $\boldsymbol{Wy}^k$ for k ranging from $\tau_{max}\ 1$ to $N - \tau_{max} - w_{max}$, are then paired in the following way:

$$\boldsymbol{Wx}^k \begin{cases} \{x_k, x_{k1}, x_{k2}, \ldots, x_{kw_{max}}\}, & \text{if } \tau \leq 0, \\ \{x_{k-\tau}, x_{k1-\tau}, x_{k2-\tau}, \ldots, x_{kw_{max}-\tau}\}, & \text{if } \tau > 0, \end{cases} \tag{1}$$

$$\boldsymbol{Wy}^k \begin{cases} \{y_k, y_{k1}, y_{k2}, \ldots, y_{kw_{max}}\}, & \text{if } \tau \leq 0, \\ \{y_{k-\tau}, y_{k1-\tau}, y_{k2-\tau}, \ldots, y_{kw_{max}-\tau}\}, & \text{if } \tau > 0, \end{cases} \tag{2}$$

and the cross–correlation between the $\boldsymbol{Wx}^k$ and $\boldsymbol{Wy}^k$ is expressed as:

$$r_\tau^k\ \frac{1}{w_{max}} \ {}_{i1}^{w_{max}} \frac{\boldsymbol{Wx}_i^k - \mu\boldsymbol{Wx}^k\boldsymbol{Wy}_i^k - \mu\boldsymbol{Wy}^k}{\text{sd}\boldsymbol{Wx}^k\text{sd}\boldsymbol{Wy}^k}, \tag{3}$$

where $\mu\cdot$ and $sd\cdot$ represent mean value and standard deviation, respectively.

In this work, for each k ranging from $\tau_{max}\ 1$ to $N - \tau_{max} - w_{max}$, we calculate the maximum of the cross–correlation:

$$r_{max}^k\ \max_\tau\{r_\tau^k\}, \tag{4}$$

and then, the mean value of every r^k_{max} is calculated as

$$r^* \quad \frac{1}{N - 2\tau_{max} - w_{max}} \, {}_k \, r^k_{max}, \tag{5}$$

which is a scalar representing the correlation between $\boldsymbol{X}$ and $\boldsymbol{Y}$.

For each participant, the r^* between their five physiological responses and the baseline signals was calculated both in the presence and absence of biosensory cues. A statistical analysis was then conducted to examine the differences in these values of r^*. If a significant difference in the r^* of a particular physiological response is observed after introducing biosensory cues, it suggests that such cues may influence physiological synchrony among participants for that specific response.

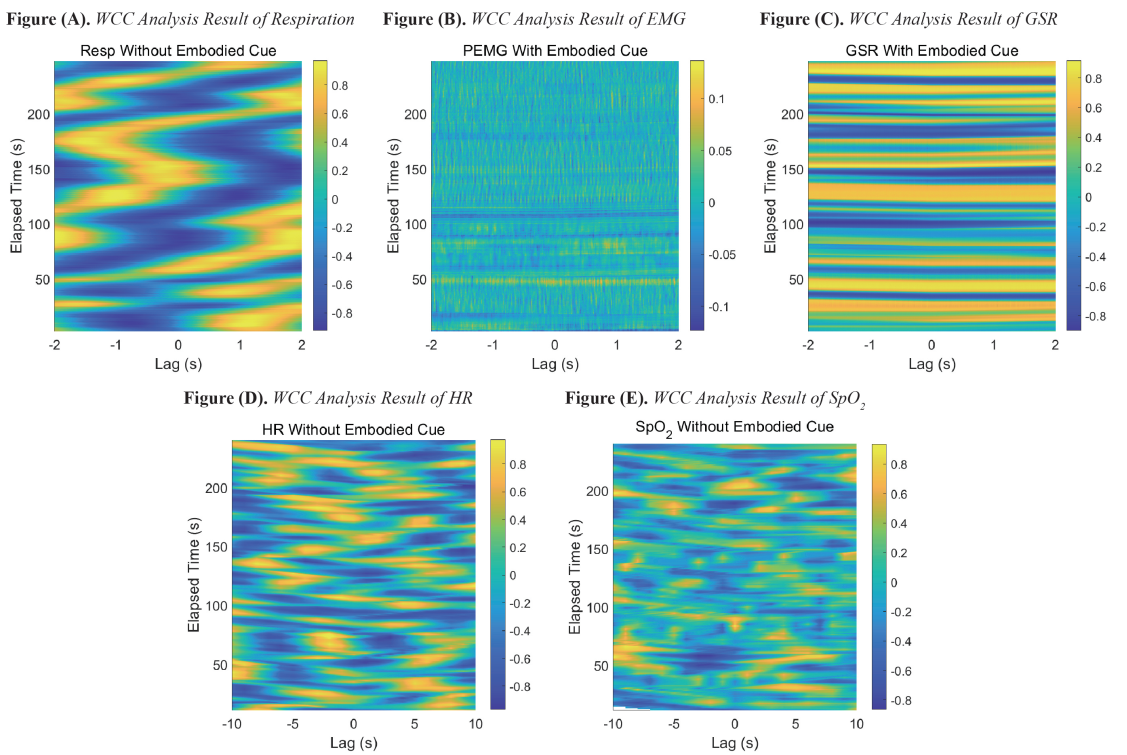

Fig. 5. WCC Analysis Result of Each Bio-signals.

3.4 Semi-Structured User Interview

After the experiment, we further invited 10 users out of the 67 participants for semi-structured interviews: 4 experts and 6 users. Experts included 2 university professors (P1 in sound engineering and DJ performance, P4 in interaction design) and 2 doctoral students (P2 in VR marketing, P3 in technology-mediated communication for the elderly). Users comprised 4 participants with high physiological synchrony results from the previous experiment (P5,P6,P7,P8) and 2 with low synchrony results (P9,P10).

The semi-structured interviews enclosed four main questions: 1) In the context of EDM, how do subjective experiences and feelings differ with and without the presence of physiological signals? Why? 2) Among the five biosensory signals (i.e., pEMG, HR, SpO_2, RE, HR), which one most potentially conveys the presence of others? Why? 3) Which of the five biosensory signals allows you to feel empathized or emotionally synchronized with others the most? Why? 4) Are there better ways to present these five biosensory signals? Any further advice or suggestions? All interviews were fully video and audio recorded after acquiring participants' acknowledgement.

We transcribed the recorded contents into texts, which were then reviewed by the team and served as the material for thematic analysis. We used a qualitative analysis software MAXQDA[2] and established a preliminary coding framework after independently coding the first three interviews. Following Braun and Clarke's guidelines [12], we conducted independent coding to enhance inter-rater reliability. Discrepancies were resolved through group discussions, achieving a consensus rate exceeding 99%.

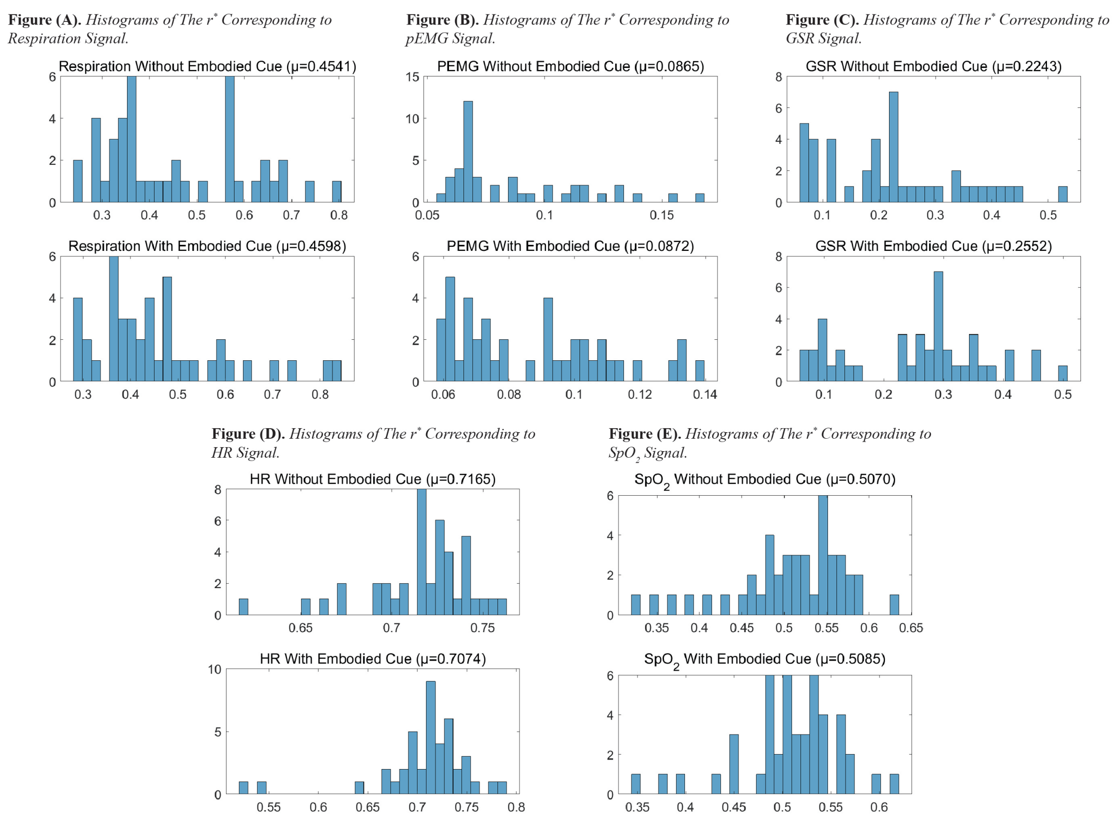

Fig. 6. Histograms of the r^* Corresponding to Bio-signal.

[2]https://www.maxqda.com

4 Results

4.1 Quantitative Results

Given that the absolute values of RE, pEMG and GSR differ significantly among subjects, and that the relative changes in these signals more accurately reflect the subjects' psychophysiological states, normalization was applied to these three signals (scaling them to a range of 0 to 1) for subsequent analysis and processing.

Taking w_{max} = 10 s and τ_{max} =2 s [11], the WCC analysis results for these five signals in comparison with the baseline signal are shown in Figures 5. The WCC of the RE signal exhibits a clear periodicity in the Lag direction, which aligns with its characteristic oscillatory pattern. In contrast, the pEMG signal displays irregularities, leading to a degree of randomness in its WCC results. Most of the other signals are generally smooth, with responses occurring only at specific moments. Consequently, these signals remain relatively stable in the Lag direction, while showing noticeable variations in the Elapsed Time direction.

Based on the WCC analysis, the r^* between each signal and the baseline signal was calculated, followed by a statistical analysis of the results. Figures 6 present the frequency distribution histograms of the r^* corresponding to the five physiological responses. Notably, the introduction of biosensory cues led to a significant increase in the r^* between participants' GSR and the baseline signal, with an average improvement exceeding 0.02.

We found that GSR, highly sensitive to emotional arousal and sympathetic nervous system changes, effectively captures physiological synchrony enhanced by biosensory cues. In contrast, RE, HR, and SpO_2 remain relatively stable, influenced more by one's own basal metabolic rates and overall ANS state, thus less responsive to short-term biosensory cue changes. pEMG signals, affected by subtle facial muscle activities, show complex variations during social or emotional interactions, leading to irregular synchrony patterns due to significant inter-individual differences.

Using WCC analysis to address **RQ1**, we found that presenting others' GSR signals can increase participants' physiological synchrony. However, HR, RE, pEMG, and SpO_2 presentations do not consistently reflect synchrony, with pEMG particularly exhibiting irregularity and randomness. The impact of biosensory cues on different physiological signals varies considerably, likely due to differences in sensitivity and response mechanisms to external cues.

4.2 Qualitative Results

Our open coding process has yielded 26 distinct codes in total, clustered into five major themes through affinity diagramming as shown in Figure 7. A network analysis (Figure 8) examined code relationships within themes, with line thickness indicating co-occurrence frequency (F). Central nodes like "Signal Meaning", "Rhythm" and "Confusion" were the most frequently mentioned codes. The five themes, ranked by mention frequency, were: 1) Bio-signals (F=55), 2) Experience Quality (F=27), 3) User Perception (F=19), 4) Potential Integration (F=15), and 5) Individual Differences (F=13).

Addressing **RQ2**, our qualitative analysis revealed that, while GSR significantly enhanced physiological synchrony (**RQ1**), user-perceived copresent experience and empathy relied more on RE and HR signals, and the two were oftentimes described as "intuitive" by the participants. This suggests enhanced physiological synchrony doesn't necessarily translate directly to higher user-perceived copresence and empathy (further explained in section 5.1).

Our subsequent discussion will present major findings synthesized from both quantitative and qualitative analyses, extracting five design implications examined in relation to existing work and established theories.

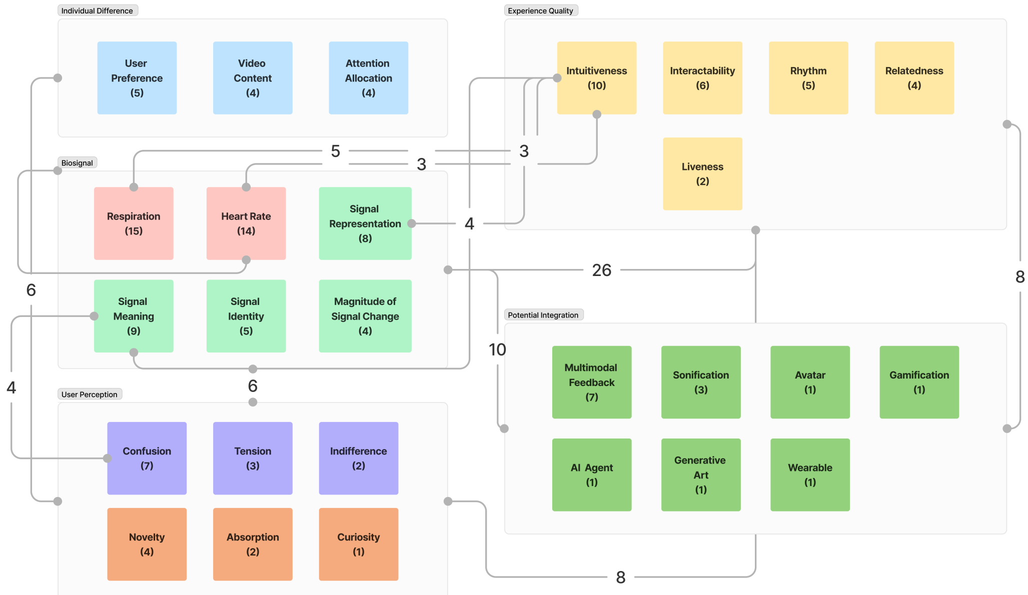

Fig. 7. Affinity Diagram Showing Codes and Major Themes.

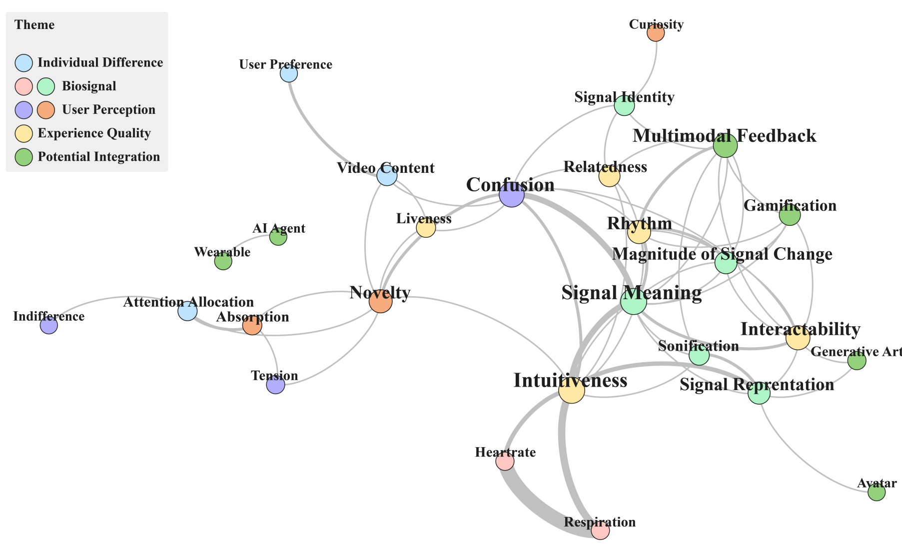

Fig. 8. Network Analysis Diagram Showing Strongest Thematic Connections.

5 Discussion

5.1 Quantitative-Qualitative Response Gap

As our most important observation, we have identified the inconsistency between the collected bio-signals and subjective user feedback. The quantitative analysis of participants' bio-data indicated that GSR outperformed the other 4 types of bio-signals regarding the physiological synchrony; while in our semi-structured interview, all participants listed RE and HR as the top two indicators of user-perceived copresence and empathy. This intriguing gap between the quantitative and the qualitative user responses contradicted with our early premise and some existing research [27, 28, 53]. Counter-intuitively, there may NOT necessarily exist a positive correlation between physiological synchrony and user-perceived copresence. However, it is yet too early to assert that they are two independent factors as it involves a rather multifaceted, complex process including how the biosensory information is presented and conveyed to the users and how the users' interpretation of the information affects the resulting copresent experience. It thus entails sophisticated design and further exploration for the biosensory cues. To this end, this research echoed some previous insights from Curran et al. [16] that although depending on the specific signal types and application contexts, visual number, graph or icon may not be a preferable presentation. This also led us to our next design implication.

5.2 Multimodal, Hybrid Data Representations

As for the biosensory cues representation, seven out of ten participants (for brevity, we will use the notation 7/10. The same applies throughout the text) had suggested multimodal stimulus, ranging from audio (P1, P2, P7), electrical stimulation (P1), haptic feedback (P8) all the way to smart devices e.g. mood light, airbags etc (P10). It implies the opportunities as well as challenges of integrating a wide range of external technologies such as sonification, wearable computing, Internet of Things etc. The pairing between a bio-signal and its representation often depends on: 1) Whether it will impose extra physical or cognitive loads on users, especially the visual representation should be cautiously designed, as porting conventional WIMP (windows, icons, menus, pointers)-based GUI into VR has been proved by previous studies oftentimes unfavorable. Specifically, several factors, such as using a WIMP interface in VR that does not follow ergonomic standards, can increase task duration, difficulty, and the level of expertise required. This often leads to greater physical and mental effort [6], which ultimately raises cognitive load and fatigue while reducing motivation [23, 48]. Therefore, biosensory cues representation should efficiently conserve users' cognitive resources, allowing them to focus on more meaningful social activities. 2) Whether it well contextualizes the use of the bio-signal with its actual application scenario in a consistent way. A such example is "jogging over a distance" by Souchet et al. [48], where HR data from geographically distant joggers were translated into spatialized audio.

One of our expert interviewees (P4, a DJ performer and sound researcher) also suggested combining biosensory cues with avatars or Emojis that also convey explicit social cues like facial expressions and body postures etc. However, he meanwhile expressed his concern that an avatar with a numerical display floating above or around its head may "*look more like an NPC in a game than a real human being*" and thus increases the risk of **depersonalization** in VR social interaction. Fundamentally, the effects of VR on dissociative experiences appear to be exacerbated by an individual's higher propensity for immersion in the virtual environment [1]; certain personal traits can also increase the inevitability of depersonalization, such as socially anxious individuals. If, on a social level, the user is burdened with the "unrealness" of the experience—feeling an overwhelming sense of virtuality caused by the "as-if" quality and uncanniness (for example, perceiving social partners as fake humans), the negative effects of depersonalization can be further amplified, further weakening the sense of presence [19].

To specifically note that, a few participants (P3, P6, P10) also emphasized that the representation should provide perceivable changes in data magnitude, regardless of different sensory channels. This may restrict the types of bio-signals to the ones that react to the stimulus more sensitively.

5.3 Cognitive Empathy + Emotional Relatedness

A significant portion (4/7) of user-perceived confusion resulted from the unclear signal meaning. Compared with raw physiological data, the participants clearly preferred some high-level, meaningful interpretations of the data. This somehow explained why all participants voted for RE and HR, the meanings of which are the most familiar and understandable. Another important aspect is the underlying personal identity associated with the signals. As P2 said, "*It triggered my curiosity, making me wonder whom these signals belong to, or even it might be a dog.*" P10's opinion further stressed this: "*It would interest me more if the data came from my friend, my family or someone I know, than from a sheer stranger.*" The participants could not make sense of the bio-data, or would even "*question about its authenticity*" (said P8, P7), if they could not relate it to themselves or other real people. Previous research by Lee et al. [32] suggested that users are intrigued by the bio-data of strangers in VR social networking but are reluctant to disclose their own bio-data, reflecting a general curiosity about others' bio-signals alongside privacy concerns regarding their own. However, in our experiment, no participants raised comments related to data privacy. We believe this may be due to the nature of our setting, where, although biosensory cues can render additional social information, they do not inherently disclose individual identity. Furthermore, cultural and regional differences in attitudes toward privacy may influence how biosensory data is perceived and shared within social VR environments.

Psychologists argued that cognitive empathy and emotional empathy are two intertwined processes that both play an irreplaceable role in prosocial behaviors [46]. This underpins our conclusion that it entails both rational understanding and emotional relatedness for users to comprehend other people's mental and physical information.

5.4 Bidirectional Regulation between Users and Bio-signals

We identified from many participants (P1, P2, P3, P4, P5, P9, 6/10) the need for an increased interactability. As P9 put it, "*I once paid attention to it (referring to the bio-signals), and tried to control it; But as long as I realized that I could not control it, I just gave it up.*" Our observation reinforced the significance of user-perceived autonomy [30] and the sense of control [9], as P1 suggested, "*at least I need to be able to choose whose signals I am watching.*" Drawing from self-determination theory (SDT) [43], our findings indicate that when individuals are unable to fully believe their choices depend on their autonomous decision-making (i.e., the degree to which an individual perceives their actions as a result of their own free will, without external interference), it becomes very difficult for them to feel psychologically free and intrinsically motivated [43]. Similarly, our stance on user control, resonating with Shneiderman's early HCI principles [54], advocates that if technological systems are unable to confer a strong sense of ownership to users and empower them as autonomous initiators with full control over their user interface interactions, it can pose significant barriers to enhancing feature utilization so that decrease overall interface quality and user experience [9]. On the other hand, biosensory cues like RE can be leveraged to regulate users via their rhythm and increase physiological synchrony (P3, P4, P5, P8). It has been practiced and proven potential in many VR mindful training already [17, 38, 44, 50]. Some studies have also used biosensory cues that are different from those in our studies and have obtained positive results. For example, Salminen et al. [44] pointed out that user responses on empathy-related electroencephalography (EEG) frontal asymmetry evoked higher self-reported empathy towards the other user than responses on respiratory activation. However, the perceived empathy was highest when both responses were presented simultaneously. Interestingly, P4 suggested that physiological synchrony may not be limited to the conventional digital bio-signals like used in this study. Other biochemical mechanisms such as semiochemicals, e.g. menstrual synchrony caused by pheromone (an although disputable, but widely perceived phenomenon [5]), should also be taken in to account as design alternatives for enhancing synchronization in VR copresent experience.

5.5 Individual Bias in Cognition and Media Use

Participants' personal preferences in media contents and use styles also had an impact on their willingness to socialize as well as how they would allocate their attention. Like P10 put it: "*I would like to interact with other audience in an idol EDM as we share a similar hobby and taste of music. But techno is not my thing.*" Also, two participants (P6 and P10) mentioned that they preferred visual information to multi-modal representation of bio-data, as other information channels may be "distracting and adding extra cognitive load". We conclude that there may be no "one-size-fits-all" solution to address this particularity that varies from individual to individual. Therefore, it can be important to provide users with options to personalize their data representation and interface.

6 Limitations and Future Work

One limitation of this study stems from our efforts to rule out potential bias introduced by extra representation of biosensory cues. To achieve this, we employed simplified visualizations of the raw bio-signal data during the experiment. However, presenting the data in a basically chart-based visualization form may have hindered participants' comprehension of the biosensory information, which was reflected in the predominantly negative feedback during user interviews, particularly for signals other than HR and RP. Additionally, the current limitations of sensor technology required both the baseline bio-signal provider and participants to be in a resting state when recording physiological data. This restriction limited our ability to capture realistic physiological responses, especially for pEMG, potentially explaining its weaker performance in the physiological synchrony analysis.

We plan to extend this work by integrating multi-channel biosensory cues that combine HR, RP, and GSR. By comparing scenarios with and without avatar-based representations of these cues, we aim to explore how different biosensory cue representations can significantly enhance technology-mediated copresence experiences. Furthermore, we will focus on conducting user-centered evaluations in real-world application environments to assess the practical effect of these cues, refining our approach to better support natural, immersive social interactions.

7 Conclusion

Recent HCI community has shown strong interests in integrating biosensory information with virtual environment. This sort of technology-mediated social interaction and sharing is believed able to alleviate some of the drawbacks of conventional avatar and verbal cues based communication, and offer an alternative paradigm to those less (socially or physically) expressive users to be connected with other people. Although with some on-going attempts, this area still calls for more empirical research efforts to systematically establish actionable guidelines and evaluation metrics.

To pave the way, this research studied and compared the effects of five different biosensory cues on users' copresent experience, by combining both quantitative and qualitative evaluations. Our finding spotted an intriguing gap between objective physiological synchrony and subjective user feedback. Explicitly, highly synchronized physiological signals did not always guarantee an enhanced user-perceived copresence, highlighting the complex interplay between quantifiable data and perceived emotional states. Based on this observation, we further proposed five design implications to provide evidence-based insight into better design and full-fledged applications of biosensory cues for future social sharing experience.

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