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Bioresponsive avatars: Perceiving emotions through virtual avatar representation in empathic social VR☆

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ABSTRACT

Social virtual reality (VR) is the experience of a shared virtual space populated by virtual representations of each individual, allowing them to communicate, collaborate and interact with each other not unlike the real world. Conventional avatars generally mirror factors like an individual's appearance, speech, movement, and so on, yet a VR can offer many more possibilities to represent a person beyond what reality can offer. One such representation is that of emotions and empathy. To that regard, we propose Bioresponsive Avatars, an avatar system that predicts user emotional states and represents them visually via their avatar appearance. To achieve this, we first conducted an avatar design workshop to understand how user's imagine emotional states to appear on an avatar. Then, we performed an in-the-wild demonstration of a social VR prototype where dyadic users are presented with affective topics to communicate while their avatars adapt based on their predicted emotions.

1. Introduction

Social virtual reality (VR) platforms like Horizon Worlds,[2] VRChat[3] and Hubs[4] enable users to socialize, collaborate, and communicate in shared virtual spaces. A key feature of these spaces is the use of avatars, which users can customize to represent themselves in various forms. The diversity of these avatars mirrors the diversity of human beings. The potential for avatars to enhance human communication, particularly in fostering empathy and understanding, remains largely untapped. Previous studies provide ample evidence that visualizing biosignals in VR and using them as social expressive cues can enhance interpersonal relationships, foster communication, empathy, engagement and feelings of connectedness [1–4]. While these works explore different visual representations of biosignals, designing avatars that can adaptively represent users' emotions inn an interpretable and non-distracting manner and understanding user perceptions within social VR environment remains unclear.

To that end, We present Bioresponsive Avatars, an emotional adaptive avatar system designed to enrich communication in VR. First, we conducted a co-design workshop with design students to determine the avatars visualization reflecting each of the emotional quadrants and establish the design guidelines that accurately and appealingly represent human emotions on the valence–arousal scale first proposed by Russell [5]. Second, we developed an experimental social VR platform utilizing Bioresponsive Avatars and exhibited in-the-wild to collect initial feedback on the visualization and its effectiveness in increasing connectedness and empathy. In summary, the contributions of this work include:

1. Co-Designed Avatar Design: The visual representation of emotions in Bioresponsive Avatars was established through a co-design workshop with design students. This collaboration resulted in avatar design guidelines that accurately and appealingly represent human emotions on the valence–arousal scale.

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1 https://tinghui-li.github.io/
2 http://www.oculus.com/facebookhorizon
3 https://hello.vrchat.com/
4 https://hubs.mozilla.com/

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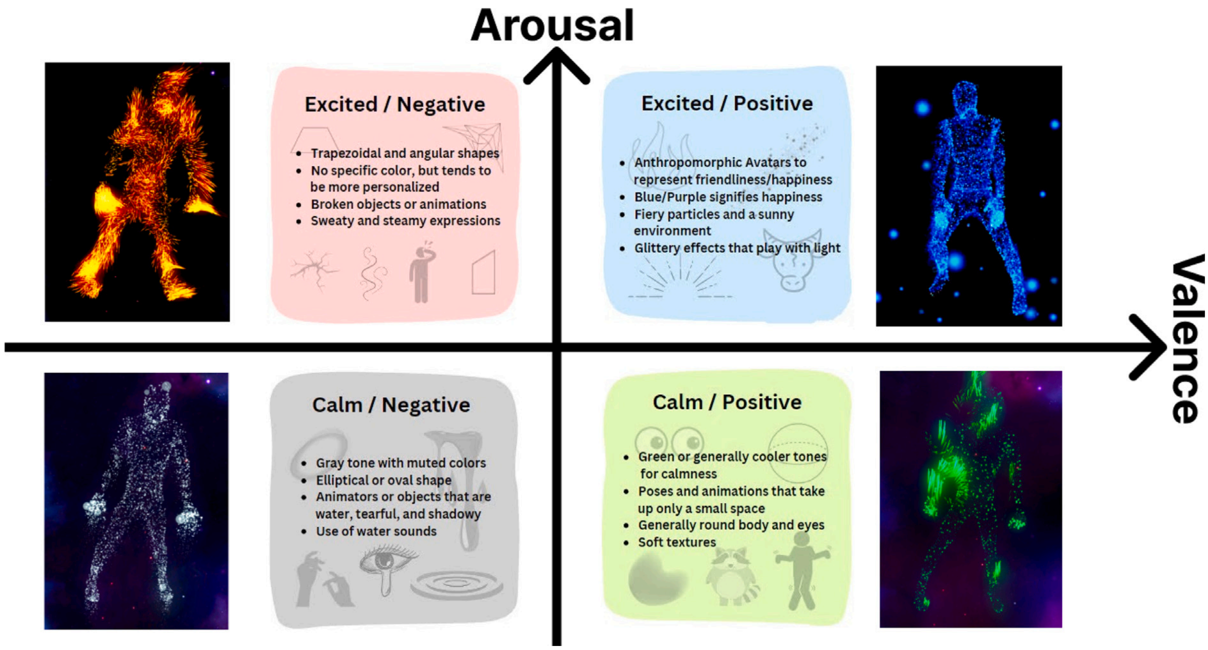

Fig. 1. A brief taxonomy on the design of Bioresponsive Avatars that covers the visual representation for avatar, environment and interaction based on the Valence–Arousal Model [5]. From here, we design our interpretation of the avatars.

2. Emotion-Responsive Avatars: Bioresponsive Avatars employs wearable physiological sensors to interpret users' emotions using the valence–arousal emotion model. This allows avatars to go beyond standard visual representations, mirroring the user's emotional state in real-time. This approach aims to deepen connections and understanding among VR participants.
3. Experimental Social VR Platform and Open Dataset: The practical application of Bioresponsive Avatars was tested through an experimental social VR platform. The results from our in-the-wild exhibition study have shown promising implications for the future of emotion-responsive avatars in social VR, indicating a potential improvement in users' ability to connect and empathize with each other. We publicly released the physiological dataset to facilitate reproducibility and future studies.

2. Related works

2.1. Empathy and social interaction in VR environments

Empathy is a multifaceted construct encompassing cognitive, affective, and compassionate dimensions [6,7]. Cognitive empathy involves understanding another person's feelings and viewpoints, whereas affective empathy concerns resonating emotionally with others. In virtual reality (VR), immersive embodiment and body ownership can amplify both forms of empathy [8], positioning VR as a powerful medium for empathy-related experiences. In the discourse on VR as an "empathy machine" Nakamura et al. [9] caution against its potential to spur toxic empathy, which is the over-identification with emotions, particularly by those in privileged positions. While VR generally enhances engagement and empathy over standard 2D mediums [10], its ability to foster specific types of empathy is debated. Some studies suggest VR enhances cognitive empathy when participants experience the perspective of a specific individual within the VR system [11]. Contrarily, others argue VR predominantly boosts emotional empathy but struggles to facilitate cognitive empathy, attributing this gap to the effortful engagement required for the latter [12]. Research has also shown that VR perspective-taking can induce long-term, empathy-driven behaviors in the real world [13,14]. Yet as VR becomes a workspace for collaboration, new social challenges emerge: users appreciate its immersive qualities but express concerns about surveillance and the authenticity of virtual relationships [15]. More recent studies integrating biofeedback in social VR demonstrate that sharing physiological signals can enhance synchrony and self-reported empathy [16,17], and affective state visualization in VR has been proposed as a tool for emotional awareness and therapeutic applications [18].

Overall, prior research confirms VR's potential to elicit empathy through embodiment, perspective-taking, and physiological feedback. However, these works largely treat empathy as an experiential outcome rather than an expressive capability of avatars themselves. The visual representation of emotion within avatars – how users' internal states can be perceptually communicated to others – remains an open question.

2.2. Emotion representation and visualization of avatars

Building upon the discussion of empathy in VR, a growing body of work explores how avatars convey users' affect for clearer social cues in XR environments. One approach modifies the avatar's appearance through dynamic visuals [18,19]. Pinilla et al. review shows that visual and sound cues can map affect into perceivable signals inside VR, which motivates designs that alter an avatar or its surrounding scene to improve emotional legibility [18]. Bernal et al. present Emotional Beasts where color, glow and aura-like elements transform the avatar to externalize internal states [19]. Another is to change the appearance of the avatar through physiological signals [20,21]. El Ali et al. discuss biosignal driven animations for social VR avatars and argue that animated cues on the body can communicate availability and affect to partners [20]. Jing et al. present a collaborative VR system that augments avatars with coordinated scene effects so teammates can interpret emotion more quickly during shared tasks [21]. Winters et al. show that listening to another person's heartbeat changes emotional perspective and raises empathic responses which supports concise sound overlays near the avatar as affective hints [22].

Recent work on sensing and mapping further informs avatar affect design. Hickson et al. used eye-tracking data to classify facial expressions and drive expressive avatars in real time [23], while Mottelson et al. demonstrated that manipulations of posture and facial expression can shape both affect and body ownership in VR [24]. Similarly, Radiah et al. found that personalization choices in avatar embodiment influence perceived emotions and social presence [25]. Despite these advances, there remains limited understanding of how co-designed, user-informed mappings between physiological signals and visual cues can foster empathy and connectedness in social VR. This motivates our exploration of bioresponsive avatars, which adapt their form and behavior based on users' real-time physiological states.

2.3. Bioresponsive avatars in extended reality (XR)

Bioresponsive avatars represent a significant advancement in XR technologies, where each user's physiological state is measured and classified into their emotional and cognitive state [26–28]. The use of physiological responses is key, as these are natural, involuntary reactions to different contexts for human beings [29]. Semertzidis et al. developed a system that enhances emotional communication between people by using brain-computer interfacing (BCI) to drive procedural content generation, which is then visualized through mixed reality as dynamic, proxemic abstract representations of affect [30]. Features such as gaze, emotion, and physiological state sharing contribute significantly to a heightened interpersonal understanding and improved collaborative results [31]. Valente et al. [32] have explored the visualization of emotions in Augmented Reality (AR), focusing on bioresponsive overlays that facilitate emotion sharing. Lee et al. [3] explored the importance of visualizing biosignals in social VR, where avatars lack non-verbal cues. Liu et al. [33] introduced the concept of expressive biosignals, experimenting with the visualization of brain signals through various graphical elements like graphs, sliders, swirls, colors, lights and emojis. Ferstl et al. [34] have discovered that certain design factors, such as head shape and eye size, can influence perceptions of trustworthiness and aggressiveness in avatars. Armstrong et al.'s [35] work on the Heightened Empathy system uses the arousal–valence emotion model along with Heart Rate Variability (HRV) and Electrodermal Activity (EDA) metrics to showcase emotions in a social XR context through avatars. Similarly, Transcendental Avatar [36] employs bioresponsive avatars driven by HRV and EDA as biofeedback to enhance cognitive states in VR.

While these works show the potential of bioresponsive systems, most remain limited to prototypes or individual affect visualization rather than shared empathic communication. This highlights the need for avatars that convey users' emotions to foster mutual awareness and prosocial connection. We envision social VR avatars that communicate richer emotional information to promote empathy and more connected social interactions.

3. Design and implement

3.1. Initial avatar design workshop

The goal of the workshop is to derive a basic avatar design language regarding how avatars should visually appear depending on emotional states. We recruited a total of 12 participants (9 females, mean = 23.75, SD = 1.64) who are design school students, and it was conducted in groups of four via Zoom[5] and Miro.[6] Each participant was first required to sign a consent form stating that the collected data will be published and no identifiable information will be collected. The workshop was initiated by asking them how they would like to have their avatar appear in a virtual world. They were given 5 min to illustrate this using their desired sketching paradigms. After that, each participant was given another 5 min to explain the reasoning behind their design to each other. This procedure was repeated four more times, where we defined an emotion of the user for each design (happy, sad, calm, and stressed, based on each of the quadrants of the valence–arousal model) and how they wished to have it reflected on their avatar. Finally, a 10 min group discussion was held where users expressed their opinions and provided feedback regarding each other's design.

[5] https://zoom.us/

[6] https://miro.com/app/

3.2. Results and discussion

An example of the sketches by the first group of four participants is shown in Fig. 2. Colors overall play an important role in portraying emotional states, evident from previous work findings as well [27,30]. When asked about an avatar appearance and form when feeling happy (positive valence and high arousal), a blueish color with friendly anthropomorphic avatars conveys this well. Particles and surround effects can also look fiery and glittery. In contrast, a sad emotion (negative valence and low arousal) can be reflected with muted tones and objects and avatars that are more elliptical. Elements of water and shadows can also be used for a sadder atmosphere. For a stressful emotion (negative valence with high arousal), angular shapes with broken effects and animations reflect this well. Avatars can also appear to look sweaty and steamy. Lastly, for calm emotion (positive valence with low arousal), a greener or cooler space paired with low-key animations is helpful. Round and soft textures also bring an element of comfort. Based on the collected results, we generated an initial guideline for the mapping of avatar and environment design according to the Valence–Arousal model shown in Fig. 1.

3.3. Interactive prototype design

Based on the guideline established from the previous workshop, we next build an interactive prototype system. We envision a social VR experience where a pair of users can view each other's avatar in real-time as they engage in affective conversations.

We focus on color representation and particle behavior to cover most of the points from the guideline. The resulting design is shown in Fig. 1. As users will directly embody these avatars, we carefully consider the mapping of movements of the user so that they can be accurately represented; if the avatars change shapes completely into non-humanoid beings, this may compromise how the avatar represents movement. Additionally, since the avatar is dynamically changing, it should appear transitional so as not to be jarring to others. Therefore, we went with a more abstract form of avatar. Depending on context, we encourage designers to explore other avatar designs that are anthropomorphic, utilize sound, and the surrounding space as well. Under the excited-negative state, the avatar appears more red hot with the particles moving with higher velocity. Under the excited-positive state, we chose a blue avatar with glittering effects. For the calm-positive state, we went with green particles that move gently and softly. Lastly, for calm-negative state, we went for a gray-toned avatar that gives the impression of a shadowy figure.

3.4. System implement

Our system is divided into three main phases: (1) physiological sensing, (2) emotion prediction, and (3) social VR. For the first phase, an Emotibit[7] sensor is strapped on the participant's index finger to collect their electrodermal activity (EDA) and heart rate variability (HRV) signals (Fig. 3(a)). During the data collection process for the machine learning model, we recruited physiological signals from 30 participants using EMotiibit wearable sensors during exposure to four 360° affective videos from a public dataset [37], with photoplethysmography (PPG) sampled at 100 Hz and electrodermal activity (EDA) at 4 Hz. Ground truth emotion labels were obtained through Self-Assessment Manikin (SAM) questionnaires [38], providing continuous valence and arousal

[7] https://www.emotibit.com/

Fig. 2. Sketches by participants in avatar design workshop.

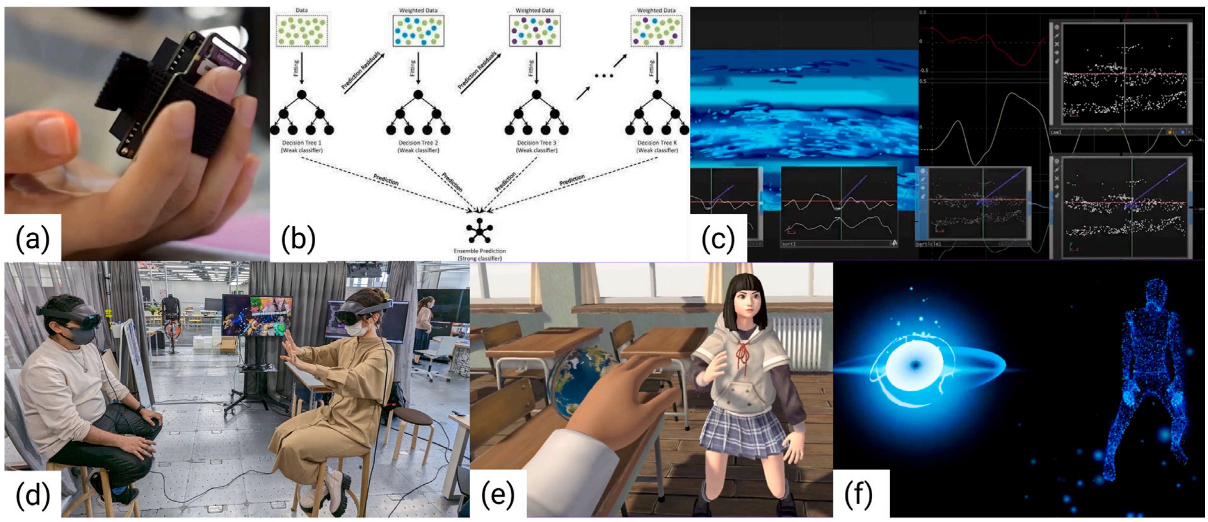

Fig. 3. (a) The Emotibit device; (b) the process of applying machine learning to physiological signals; (c) real-time physiological signal transmission using TouchDesigner; (d) recording of the two-person scenario test; (e) a first-person view of a participant in Scenario 2; (f) the interface of the bioresponsive system, where users can view their physiological avatars and the orb representing the emotional states of the participants.

ratings subsequently discretized into four classes following Russell's circumplex model: High Valence-High Arousal (HVHA), High Valence-Low Arousal (HVLA), Low Valence-High Arousal (LVHA), and Low Valence-Low Arousal (LVLA) using median-split thresholding [5]. The 100 Hz PPG sampling rate was selected to provide adequate temporal resolution for heart rate variability analysis while maintaining computational efficiency, with EMotiibit's integrated sensor configuration ensuring synchronized multimodal data acquisition.

Then, in the second phase, these signals are processed by using the NeuroKit2[8] library, with PPG signals initially filtered using a Butterworth bandpass filter ($0.5 - 8$ Hz) to remove baseline drift and high-frequency noise while preserving pulse morphology. Artifact detection and removal employed the Elgendi method, which utilizes dual moving averages with adaptive thresholding to identify physiologically implausible peaks and motion artifacts. This approach demonstrates superior performance in naturalistic viewing environments compared to traditional peak detection methods. The Elgendi algorithm applies short-window (0.11 s) and long-window (0.67 s) moving averages with dynamic thresholding set at 0.02 ×(shortMA - longMA), incorporating physiological constraints (40-200 BPM) and morphological validation criteria to ensure signal quality. Heart rate variability features were extracted from cleaned PPG signals using established time-domain, frequency-domain, and non-linear metrics. Time-domain features included RMSSD (root mean square of successive RR differences), pNN50 (percentage of RR intervals differing > 50 ms), and SDNN (standard deviation of RR intervals), providing indicators of parasympathetic activity and overall autonomic function. Frequency-domain analysis computed low-frequency (LF : $0.04 - 0.15$ Hz) and high-frequency (HF : $0.15 - 0.4$ Hz) power components along with their ratio, representing sympathetic-parasympathetic balance and pure parasympathetic activity respectively. Non-linear features comprised sample entropy and Poincaré plot metrics (SD1, SD2) to capture signal regularity and geometric HRV characteristics. Concurrently, EDA signals underwent tonic-phasic decomposition to separate slow-changing baseline conductance (> 1 s) from fast-changing sympathetic responses (< 5 s), with extracted features including skin conductance response frequency, amplitude, rise time, and mean tonic level [39].

A sliding window approach with 30-second segments and 50% overlap was implemented to balance temporal resolution with statistical reliability for feature extraction. The 30-second window duration was selected to encompass 54 heartbeats necessary for robust HRV analysis while capturing complete emotional response dynamics typically occurring within 5–30 seconds [40].

Windows of length $L = 30\,\text{s}$ with hop $H = L/2 = 15\,\text{s}$. For a video segment of duration T,

$$N_{\text{win}} = \left\lfloor \frac{T - L}{H} \right\rfloor + 1.$$

For each window w, assemble feature vector

$$\mathbf{z}_w \in \mathbb{R}^D, \quad D \approx 25\text{–}30,$$

The 50% overlap strategy ensured continuity in emotion tracking, increased training sample availability, and reduced edge effects in feature computation. This windowing scheme generated a comprehensive feature vector of approximately 25–30 dimensions per window, combining HRV time-domain (8 features), frequency-domain (6 features), and non-linear metrics (4 features) with EDA-derived parameters (6–8 features) [41].

[8] https://neuropsychology.github.io/NeuroKit/

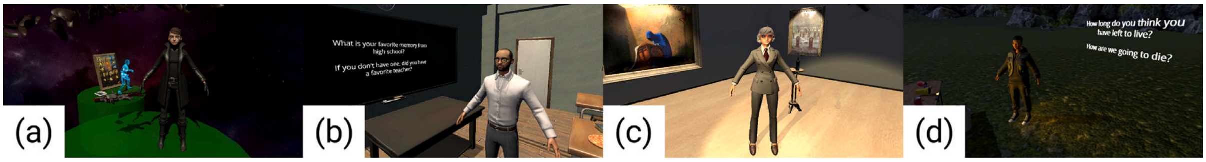

Fig. 4. From left to right are Scenario 1, Scenario 2, Scenario 3, and Scenario 4, each accompanied by a corresponding avatar designed to match the thematic context of the scene.

Per-participant datas were fed into a machine learning model trained using a Gradient Boosting Classifier (Fig. 3(b)) to account for individual physiological variability in baseline heart rate, EDA levels, and autonomic response patterns, which can vary 2–3 fold between individuals [35,42].

The overall supervised pipeline per participant:

$$x_{\text{raw}} \xrightarrow{\text{filter+clean}} (RR,\, T,\, P) \xrightarrow{\Phi} \mathbf{z} \xrightarrow{f^{(p)}} \hat{c},$$

where Φ stacks HRV (time, frequency, non-linear) and EDA features; $f^{(p)}$ is trained under LOVO with SAM-derived quadrant labels.

This personalized modeling approach addresses variations in sensor coupling, movement artifacts, and psychological factors such as emotion regulation strategies. Leave-one-video-out cross-validation was employed to ensure temporal generalization capability, with model performance evaluated using 4-class accuracy metrics. The resulting per-participant models achieved an average classification accuracy of 87.73% across the four emotion quadrants, demonstrating the efficacy of this multimodal physiological approach for naturalistic emotion recognition in immersive video environments.

We used Touch Designer[9] to collect the signals and run the real-time prediction model (Fig. 3(c)). The predicted output are then piped to Unity[10] for VR interaction. This brings us to the third phase, where two participants are brought into a shared social VR space (Fig. 4(d)). The social VR environment is developed using the Unity game engine, whereas the multiplayer components use the Normcore[11] plugin. As both participants put on the Meta Quest Pro headset, they are brought into one of the four scenarios shown in Fig. 4 where they are required to converse with each other based on a provided topic (Fig. 4(e)):

Scenario 1 (high arousal, low valence): We designed a post-apocalyptic sci-fi environment to evoke a sense of desolation, stress and nervousness (Fig. 4(a)). The prompt sentence presented here is "AI is being used more frequently in the commission of crime and fraud. Who should be held responsible?"

Scenario 2 (high arousal, high valence): We designed a classroom environment filled with the bustling of happy students with a bright atmosphere (Fig. 4(b)). The prompt sentence here is "What is your favourite memory from high school? If you don't have one, did you have a favourite teacher?"

Scenario 3 (low arousal, high valence): We designed an art gallery that is peaceful, thought-provoking, and relaxing (Fig. 4(c)). The prompt sentence here is "Think of a meaningful person in your life. What is something meaningful that they taught you?"

Scenario 4 (low arousal, low valence): We designed a quiet, dark camp in a forest to evoke a sense of sadness, depression and loneliness (Fig. 4(d)). The prompt sentence here is "How long do you think you have left to live? How are we going to die?"

9 https://derivative.ca/
10 https://unity.com/
11 https://normcore.io/

4. Evaluation study

4.1. Procedure

Based on the physiological dataset collected from 30 participants, we developed personalized emotion prediction models for each individual. In the live experiment, two participants were invited to independently watch two 360° affective videos selected from the same public dataset. During the viewing, we collected their EDA and heart HRV signals. Using these signals, we calibrated individual emotion models tailored to each participant. During the subsequent social VR interaction, the participants' emotional states were continuously estimated and updated every 30 s based on their real-time physiological signals.

Two participants are randomly assigned to one of the four social VR scenarios and begin a 2-minute conversation guided by contextual prompts. They are then transitioned into the Bioresponsive Avatars environment, where an orb and their physiological avatars are displayed to visualize how their emotional states synchronize. After this phase, the participants are redirected to another 2-minute conversation in one of the VR scenarios, followed by a final return to the Bioresponsive Avatars system. As shown in Fig. 3(f), if the participants increasingly synchronize emotionally, meaning they share similar emotional states for most of the interaction, the orb gradually transforms into a fully grown tree.(as Fig. 5(c)).

4.2. Exploratory session in-the-wild

The goal of this exploratory session is to obtain initial quantitative and qualitative feedback regarding the experience of participating in a social VR platform with Bioresponsive Avatars where affective communication takes center stage. To achieve this, the interactive prototype was demonstrated in a large exhibition hall showcasing emerging VR technology. As this is not a controlled setup, we are not expecting to gather comparative results with a baseline condition. Instead, it is to provide real-world experience to users regarding how Bioresponsive Avatars can directly influence communication (see Fig. 6).

The exhibition booth is 4 m by 4 m with two large displays connected to a desktop computer powered by an NVIDIA RTX 3080. A Meta Quest Pro is also connected to each of the desktop via a link cable. When a pair of attendees enter the booth, they are first required to sign a consent form stating that they are willing to participate and provide data, as well as allowed to have photos and videos taken and shared. The exhibitor then explains the system and the task that will be presented to them. Afterwards, the exhibitors assist them with putting on the sensors as well as the HMD. A 3-minute calibration phase is initiated, where we present affective 360° videos from a publicly available dataset [37] while collecting their PPG data. This PPG data is used to retrain the model and improve its performance. Once the calibration is completed, the first scene plays, which will be randomly assigned based on one of the four pre-made scenario and topic. Once the demonstration was complete, we had each attendee answer a set of prepared questionnaires (State empathy scale [43] and experience feedback).

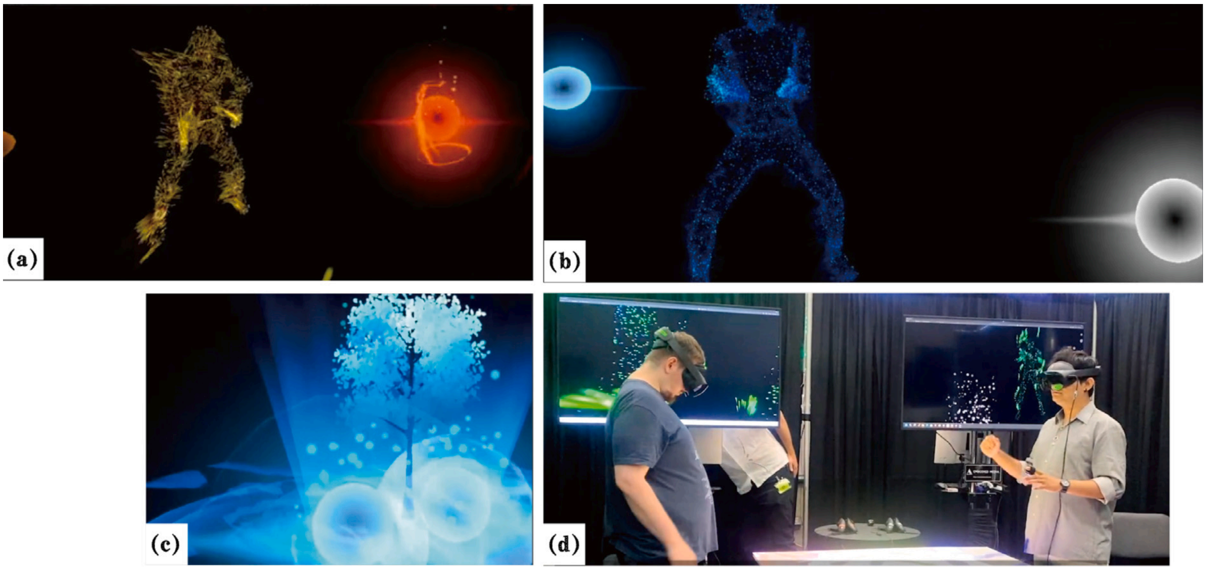

Fig. 5. (a) A user's bio-avatar in the excited-negative state; (b) a user's bio-orb in the calm-negative state, while his partner is in the excited-positive state; (c) when both users are in the excited-positive state, their bio-orbs converge at the center and a tree representing empathy begins to grow; (d) two users interacting within the Bioresponsive Avatars experience.

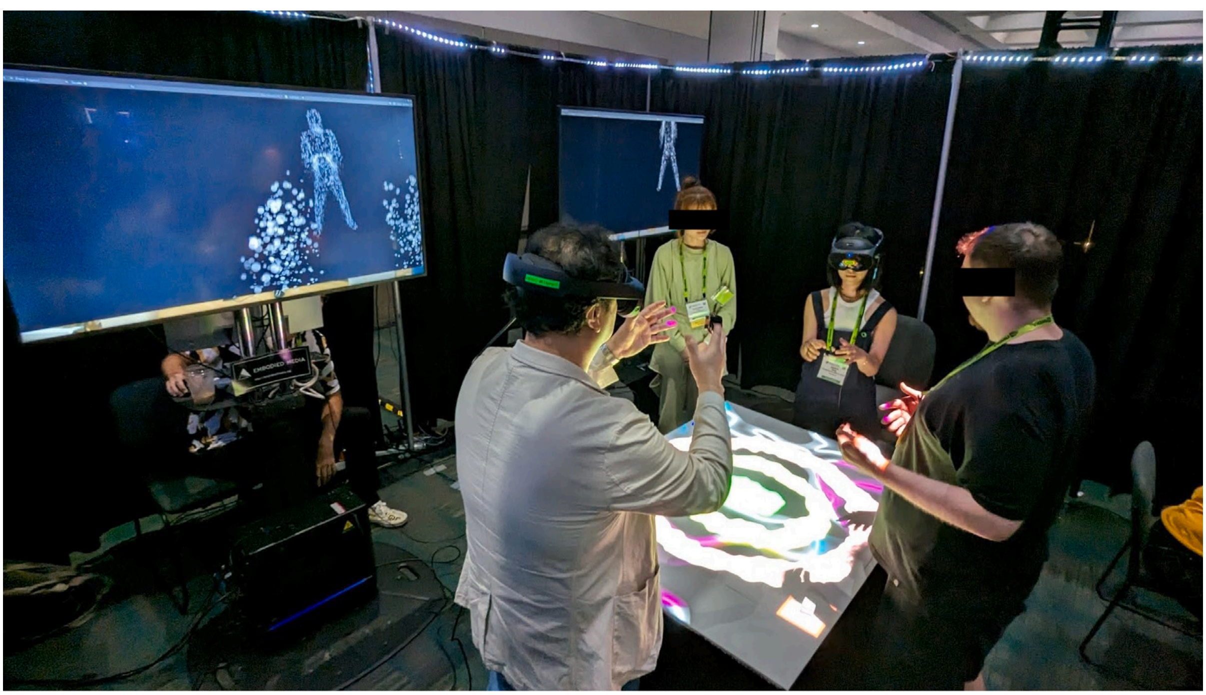

Fig. 6. Exploratory session to the general public to experience the prototype.

4.3. Participants

We recruited participants through an in-the-wild exhibition, which lasted for five days and attracted over 100 attendees to try out the system. After filtering out incomplete data, we retained valid responses from 55 participants(M = 24, F = 30, Other = 1). Due to the public nature of the exhibition setting, it was challenging to ensure that all attendees completed the tasks or answered the questionnaire as intended. For age distribution, 9.1% were between 19 and 24 years old, 32.7% were between 25 and 31, 27.3% were between 32 and 38, and another 27.3% were over 39 years, while 5.5% preferred not to disclose their age.

4.4. Method

We conducted qualitative analysis using systematic on-site observations to capture participants' in-site behaviors, complemented by post-experience questionnaires and short interviews. All qualitative data – including field notes, open responses, and interview transcripts – were analyzed through inductive analysis to identify recurring themes and patterns in the experiences of the participants.

5. Findings and discussion

Based on observation data, post-experience reflections, and interview excerpts, we identified three key themes – cognitive, affective, and associative dimensions of empathy – that inform the future design of emotionally sensitive avatars and emotion-aware VR systems.

5.1. Enhancing emotional connectivity intuitive emotional representation

Many participants responded positively to the system's visual expressiveness and emotional embodiment. The dynamic avatar transformations, particularly the color changes and particle effects, were frequently described as engaging and aesthetically pleasing. P8 felt, "Cool!",P27 said "The avatar visualizations were very cool! Loved the particle effects and color"., and P33 said "Very cool and unique experience. I would love something like this for team bonding". These responses suggest that participants perceived the bioresponsive avatars not only as functional emotional representations but also as visually enjoyable elements of the social VR experience [44,45]. Participants' generally positive responses to the avatar's nuanced emotional expressions hint that clearer affective representations could play a role in supporting empathy in social interaction [46]. This trend is broadly in line with prior work suggesting that engaging aesthetics may contribute to immersion and emotional resonance in XR [47,48].

5.2. Toward empathic interaction: Effects of varied bio-responsive design

Some participants reflected on how the system influenced their perception of emotional states—both their own and their partner's. For example, Participant P5 reported feeling that they understood their partner better after the session, suggesting that the bioresponsive system may contribute to empathic engagement and emotional connection under certain conditions [3,49]. In individual cases, such as P14's remark, "Fun experience! I wonder why I was negative-positive!", even when users were unsure about how their emotional state was being classified, the visual feedback served as a stimulus for self-reflection and emotional awareness [50].

Bioresponsive Avatars appeared to shift participants' perception of conversation from a task driven interaction to a more emotionally meaningful act, motivating them to engage in deeper reflection rather than merely responding to prompts. The VR system scaffolded multiple phases of interaction, from guided conversations to transitions to abstract biofeedback environments, creating opportunities for affective exchange and introspection [51–53]. Some participants became more attuned to the relational and emotional dimensions of the dialogue [54, 55]. These findings suggest that varying interaction modalities, such as scenario-based conversations and ambient biofeedback visualizations, can improve emotional resonance [56] and may be applicable to broader contexts, such as remote collaboration, interpersonal training, among participants [57,58].

5.3. Fostering a sense of community through shared emotional experiences

Participants engaged with the experience in pairs, and many commented on the shared quality of the emotional space, particularly when the visual feedback revealed moments of synchrony. The transformation of the orb into a tree, which occurred as emotional synchrony increased, served as a symbolic and collective emotional goal. This mechanism appeared to cultivate mutual awareness and interdependence, encouraging participants to attend not only to their own states but also to their partner's.

These observations support the integration of features that enable users to interact, share experiences, and foster a sense of community. While further controlled studies are needed to substantiate these findings, the use of bioresponsive avatars appeared to enhance social connectedness and interaction within the shared VR environment [57]. This suggests the potential of bioresponsive avatars to foster a sense of community through shared emotional experiences.

6. Limitations

While the in-the-wild setting enhanced ecological validity, the study faced limitations in controlling the total duration of the user experience. Variability in setup time, participant pacing, and environmental distractions occasionally led to shortened or uneven engagement across participants. In addition, the emotional calibration phase, which is critical for personalizing the bioresponsive feedback, was constrained by time and content. Some participants reported that the selected affective stimuli (e.g., Fukushima 360° video) failed to elicit strong emotional responses, suggesting that more emotionally potent or personalized stimuli (e.g., rollercoasters or horror scenarios) may be more effective in initiating affective engagement. These factors may have influenced the system's ability to accurately reflect users' emotional states during the interactive phases. Future work should also take into account cross-cultural variability in emotional perception and expression, which may shape how users respond to affective stimuli and biofeedback systems.

7. Conclusion and future works

This work presents Bioresponsive Avatars, a bioresponsive avatar system designed to enhance emotional awareness and communication in social VR environments. By visually reflecting users' affective states through co-designed, emotionally responsive avatars, the system encourages empathy, shared presence, and deeper interpersonal connection [59]. Through an in-the-wild deployment, we observed how the dynamic visualizations supported intuitive emotional understanding and prompted participants to reflect on both their own and their partner's emotional states [60].

Our findings highlight that emotionally expressive avatars can act as effective mediators of social connection [61–63]. The system's ability to visualize emotional synchrony, as seen in the transformation of the orb into a tree, helped to reinforce mutual awareness and foster a sense of shared emotional space [64]. The feedback of the participants highlighted the potential of the system for broader applications, including team bonding, collaborative work, and emotionally tuned virtual meetings [65].

Future iterations of the system should incorporate more emotionally evocative and culturally diverse stimuli to improve initial affect induction. Furthermore, clearer interpretability of biofeedback may enhance user trust and engagement [66–69]. For future work, we plan to conduct a controlled comparative study to rigorously evaluate the impact of bioresponsive avatars against baseline conditions. In addition, we will explore the application of Bioresponsive Avatars in varied social VR contexts, such as professional meetings, remote learning, and empathic training sessions [70].

In summary, Bioresponsive Avatars contributes a co-designed emotional avatar visualization framework grounded in the valence–arousal model, a functional prototype of bioresponsive avatars that leverages real-time physiological signals within a social VR context, and empirical insights from an in-the-wild deployment that underscore the importance of shared emotional experiences in fostering empathy and community among users [71]. These findings underscore the potential of bioresponsive avatar systems to shape the future of emotionally intelligent virtual communication. This work also introduces a multimodal physiological dataset collected during the study, which we have made publicly accessible for further research and replication.

CRediT authorship contribution statement

Danyang Peng: Writing – review & editing, Writing – original draft, Validation, Software, Conceptualization. **Zicheng Xia:** Data curation. **Tinghui Li:** Writing – review & editing. **Yixin Wang:** Conceptualization. **Mark Armstrong:** Visualization, Software. **Kinga Skierś:** Visualization. **Anish Kundu:** Writing – review & editing. **Kouta Minamizawa:** Supervision. **Yun Suen Pai:** Supervision.

Declaration of competing interest

The authors – Danyang Peng, Zicheng Xia, Tinghui Li, Yinxin Wang, Mark Armstrong, Kinga Skiers, Anish Kundu, Kouta Minamizawa, and Yun Suen Pai – (paper ID: 2711) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

All authors confirm that there are no concurrent submissions or undisclosed collaborations related to this work and agree to its submission to the journal.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.cag.2025.104474.

Data availability statement

The datasets generated and analyzed during the current study are available in the supplementary file "Bioresponsive Avatars Dataset.zip". All data have been anonymized and processed prior to publication. The experimental protocol was reviewed and approved by the Ethics Committee of Keio University Graduate School of Media Design. For any further inquiries, please contact the corresponding author.

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