Understanding and Designing Avatar Biosignal Visualizations for Social Virtual Reality Entertainment

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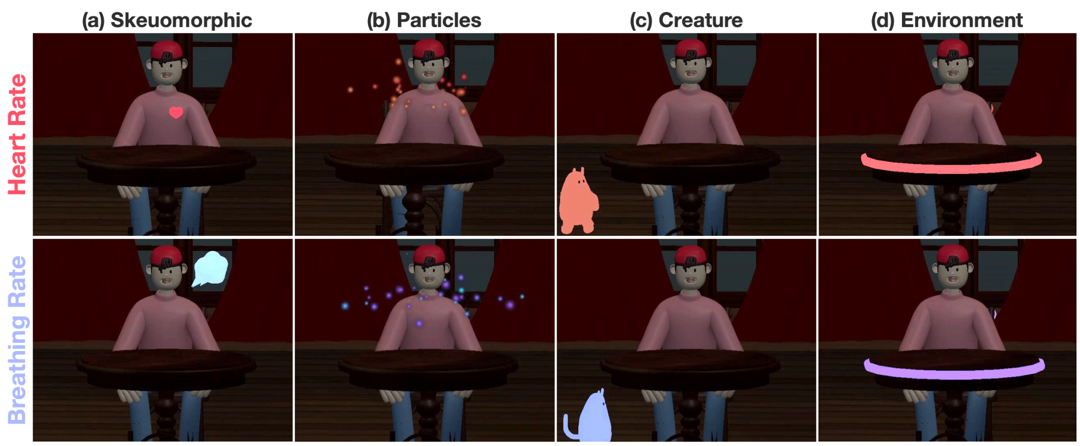

Figure 1: Our Unity-based visualizations for heart rate (top) and breathing rate (bottom).

ABSTRACT

Visualizing biosignals can be important for social Virtual Reality (VR), where avatar non-verbal cues are missing. While several biosignal representations exist, designing effective visualizations and understanding user perceptions within social VR entertainment remains unclear. We adopt a mixed-methods approach to design biosignals for social VR entertainment. Using survey (N=54), context-mapping (N=6), and co-design (N=6) methods, we derive four visualizations. We then ran a within-subjects study (N=32) in a virtual jazz-bar to investigate how heart rate (HR) and breathing rate (BR) visualizations, and signal rate, influence perceived avatar arousal, user distraction, and preferences. Findings show that skeuomorphic visualizations for both biosignals allow differentiable arousal inference; skeuomorphic and particles were least distracting for HR, whereas all were similarly distracting for BR; biosignal perceptions often depend on avatar relations, entertainment type, and emotion inference of avatars versus spaces. We contribute HR and BR visualizations, and considerations for designing social VR entertainment biosignal visualizations.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; • **Virtual Reality**;

KEYWORDS

Biosignals, social VR, visualization, entertainment, virtual reality, perception, design

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1 INTRODUCTION

As social creatures, we typically draw on a wide range of visible non-verbal behavioral cues (facial expressions, gestures, etc.) to form impressions and facilitate communication with one another [25, 32, 48, 78]. Despite their importance on the interpersonal communication process [1, 25, 48], it remains a fundamental challenge for digitally mediated communication where several such cues are missing [47, 102]. Recent technological advances have shown that it is possible to reveal previously invisible physiological data ("biosignals") about others to better inform our impressions. These biosignals can provide useful insights to others about our internal emotional and cognitive states, where social sharing of such data allows others to peek into our normally hidden experiences. To this end, researchers have shown that "expressive" biosignals [53], where an individual's biosignals are displayed as a social cue, have the potential to enhance inter-personal communication and increase our interoceptive awareness [29, 62], by allowing us to better recognize others' and helps express our own emotional and physical state [24, 27, 43, 45, 53, 55, 56, 67, 87]. Prior research has shown that a person's heart rate (HR) rises and falls with fluctuations in their emotions [49], children's skin conductance is influenced with heightened engagement [42], or respiratory rate changes during cognitive load [34]. Together, these studies provide ample evidence that visualizing biosignals and using them as social expressive cues can enhance interpersonal relationships and feelings of connectedness [24, 56].

Recently, the wide availability of consumer head-mounted displays (HMDs) has made immersive virtual reality (VR) systems a feasible alternative to 2D video conferencing. With VR, people are able to "meet" in a shared, immersive virtual environment and interact with virtual representations of each other. Such environments are denoted as collaborative or social VR [18, 41, 51]. The virtual representations in social VR can map a user's movement onto an avatar (e.g., VRChat) and/or show believable facial emotional expressions [12], whereby personalizing avatar representations has been shown to impact immersion [101]. Much research has shown the benefits of non-verbal communication in social VR, from eye gaze [28] to facial expressions [5], given the importance of realism and presence in such environments [46]. Similarly, several research strands have explored the influence of biosignals within social VR and how it can better foster communication, empathy and engagement. Halbig et al. [36] identified use cases where biodata could improve the quality of interaction in VR, where ordinarily implicit bodily information remains invisible during avatar encounters. Janssen et al. [45] showed that heartbeat perception influences social behavior in a similar manner to more common signals such as gaze and interpersonal distance. Ceenu & Hassib [30] investigated different biosignal representations (from glowing avatars to text) for HR in a social VR game. While these works explore different (visual) representations of biosignals, designing interpretable and non-distracting visualizations, and understanding user perceptions within social VR entertainment remains unclear.

In this paper, we adopt an exploratory, mixed-methods approach (Figure 2) that combines a user-centric process [71] and statistical methods to better understand, design, and evaluate expressive biosignal visualizations for social VR entertainment. In Part 1, we ask: **(RQ1a)** What are users' current perceptions toward virtual avatar representations and biosignals in social VR spaces? **(RQ1b)** What are the most suitable ways of visualizing users' biosignals in social VR entertainment spaces? For RQ1a, we draw on survey responses (N=54) and a follow-up context-mapping [98] interview session (N=6) to gather insights on users' current behavior and attitudes towards avatars and biosignals in social VR spaces. Drawing on these findings, we proceed to RQ1b, where we ran an online expert co-design session (N=6). These were guided by seven design considerations distilled from the survey and context mapping sessions, which resulted in three entertainment scenarios and six suitable biosignal visualization concepts. Thereafter, we prototyped the four most suitable visualizations (Figure 1) for HR and BR for display in a virtual jazz bar scenario (Figure 6). This lead to our second question (Part 2): **(RQ2)** Which are the most effective visualizations of HR and BR biosignals in an immersive, virtual music event scenario? To answer this, we ran a controlled, within-subjects experiment (N=32) with pairs of users to investigate the effects of biosignals (Heart Rate vs. Breathing Rate), visualization (Skeuomorphic vs. Particles vs. Creature vs. Environment), and signal rate (Low vs. Rest vs. High) on perceived avatar arousal, user perceived distraction, and overall preferences. Key findings showed that (a) skeuomorphic visualizations for both biosignals allow differentiable arousal inference (b) skeuomorphic and particles were least distracting for HR, whereas all were similarly distracting for BR (c) biosignal perceptions often depend on perceived avatar relationship, entertainment type, and whether emotions are inferred for avatars or spaces.

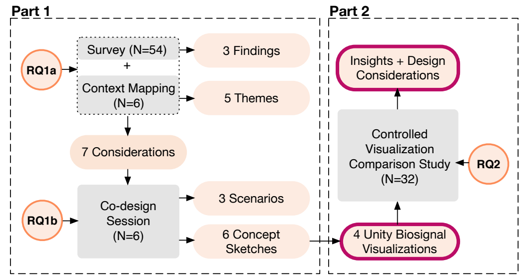


Figure 2: Our two-part study approach. Contributions outlined in (bold) magenta.

Our work offers two primary contributions: **(1)** We provide a set of empirically tested social VR biosignal visualizations[1] for HR and BR data, designed through a user-centric process that was statistically evaluated in a controlled user study. **(2)** We provide empirically-backed insights and design considerations for visualizing avatar biosignals, specifically for building HR and BR visualizations that are interpretable, suitable, and least distracting in an entertainment-based social VR scenario. Below we start with a survey of related work.

2 RELATED WORK

Several research strands influenced our approach, which we describe below.

[1] GitHub: https://github.com/cwi-dis/CHI2022-AvatarBiosignalVisualizations

2.1 Making sense of biosignal representations

It is becoming increasingly clear that digitally manifesting human biosignals can increase engagement and reduce stress [35], increase bodily awareness [97], influence social behavior [45] and trust [66], increase intimacy and enable more authentic communication [56] and heightened co-presence [24], and elicit empathy and social connectedness [17, 55, 105]. Despite the foregoing, the sensing modality (e.g., ECG), the context where biosignals are used (e.g, self or other), and how they are visualized (e.g., heart icon) [58] can impact their interpretation. Prior work has shown that biosignals are inherently ambiguous and open to multiple interpretations [43], and this can influence how (which modality) [40] and when they are shared ([56]). For example, Merrill et al. [65] found that people tend to make negative inferences even about normal (rather than elevated) heart rates, when perceived in an adversarial setting. Such ambiguities can also be traced to how humans perceive stimuli, for example Wiens et al. [93] found that good heartbeat detectors reported more intense emotions than poor detectors when viewing varying emotional stimuli, suggesting differences across human visceral perception. Finally, sharing and perceiving biosignals has been recurrently found to pose privacy concerns for users, for example when sharing HR [53, 90] or breathing [27] data. Given the foregoing, it becomes paramount to consider the most effective means of visualizing biosignals, and their usage context. This would help ensure minimal ambiguity on what they signify. In this work, we test our visualizations in a moderate socially engaging entertainment setting, and investigated perceived avatar arousal differences among our HR and BR visualizations.

2.2 Visualizing human biosignals

Visualizing human biosignals has a rich history within HCI, where the type of manifestation is largely contingent on the situation and social context [58]. For such representations, researchers have explored several visual and non-visual representations (primarily for HR), and include: ambient light [53, 91], clothing color change [43], graph-based [54, 66, 100], patterned image overlays [90], skeuomorphic [15, 26, 33, 50, 62] and text/numerical [30, 54, 62, 69, 97, 100] HR representations, abstract shapes [30, 33, 55, 87], screen overlay color [2, 30, 33, 39, 55, 97], brightness and frequency [27], haptics [67, 104], auditory heartbeats [19, 97, 105], interactive (game) element adjustment [68, 94], tangibles [31], wearable skeuomorphic artifacts [21], emojis [53], fur-based and particle systems on avatars [11], realistic blood flow animations [63], and animated creature embodiments (motion) [55, 56]. We refer the reader to Lux et al.'s [58] comprehensive literature review of different biosignal representations. While these works explore different (visual) representations of biosignals, comparative analyses (e.g., [30, 53]) across signals and visualization methods are rare. Given this, it remains a challenge to determine the most appropriate means of visualizing expressive biosignals, and specifically how users interpret them within social VR entertainment. Moreover, while prior work typically dealt with one biosignal representation and explored its impact on perception (cf., HR in [54]), our work contributes a user-centric approach where several common biosignal representations are systematically explored.

2.3 Biosignals in (social) XR

Over the recent years, there have been several works exploring the potential of affective visualizations [72, 88] and biosignals in eXtended Reality (XR) environments, where increasing evidence shows the potential of combining VR and biofeedback to foster empathic abilities in humans [85]. These works range from collaborative mixed reality [37, 62], cooperative virtual reality games [38, 73], neuro-responsive social VR using EEG to evoke empathy [82, 83]) or regulate emotion [87], VR-based breathing synchronization to foster connectedness [94], to how HR feedback manipulation helps better understand the effects of shared biosignals in collaborative VR [19]. Closer to our present work, Ceenu & Hassib [30] investigated different biosignal representations (from glowing avatars to text indicators) for HR in a playful collaborative social VR game, and found that the aura visualization was most enjoyed. Chen et al. [15] tested different multimodal HR representations of one's own HR data (so not social VR), and found audio-haptic feedback was the most preferred while visual feedback was reported as being distracting [15]. Gradl et al. [33] tested different HR visualizations in VR, and found a pulsating screen overlay was best for assessing cardiac interoceptive awareness. Lastly, Li et al. [50] explored how HR can be used as a chronemic cue in social VR, and found that varied HR can lead to higher perceived avatar arousal. These previous works helped ground the design of our visualizations, and provide a basis to further explore how different visual representations of biosignals may look like and how they are perceived in social VR entertainment.

3 PART 1: UNDERSTANDING AND (CO-)DESIGNING SOCIAL VR BIOSIGNALS

3.1 Survey: understanding current social VR experiences

We conducted a survey to better understand current social VR platform usage and experiences. The survey took approximately 10-15 min. to complete, and was distributed across social media platforms (Twitter, Reddit, etc.) in March, 2021. Several responses (over 100) were manually classified as spam (duplicate responses removal, filtering out identical emails filled, inspecting respondents' open field responses) by the study authors, and thereafter omitted from analysis. A lottery-based compensation of €30 was offered to one respondent.

3.1.1 Questions. After demographic questions and general VR experiences (e.g. owning VR headset, usage frequency, etc.), respondents had to select one social VR platform that they want to base their subsequent responses on given variations across social VR platform experiences. Next, using 5-point Likert scale questions, respondents were asked about their avatar customization experiences, and their attitudes regarding current avatar appearance and how well they represent them. They were further asked about their avatar emotion inferences, and biosignal sharing attitudes towards (a) a real-life friend (b) a virtual friend (c) a virtual stranger. The survey included more questions relating to social VR experiences, however here we focus only on questions that pertain to biosignals.

Question	Md	IQR
The avatar I use the most represents my identity in the social VR space.	4	2
I (want to) put effort into customizing avatars to reflect my identity in the social VR space.	5	1
I prefer to customize my avatar as an 'ideal' version of myself instead of reflecting how I look like in real life.	4	3
It is easy to recognize other avatars' emotions.	3	2
In general, I want to hide my real biological signals (e.g., heartbeat, breathing rate) when interacting with:		
...an 'actual real-life friend' in social VR (N=31)	3	2.5
...a 'virtual friend' in social VR (N=39)	3	2
...a 'stranger' in social VR (N=48)	4	3

Table 1: A selection of the 5-point Likert-scale questions that we asked in our survey (N=54).

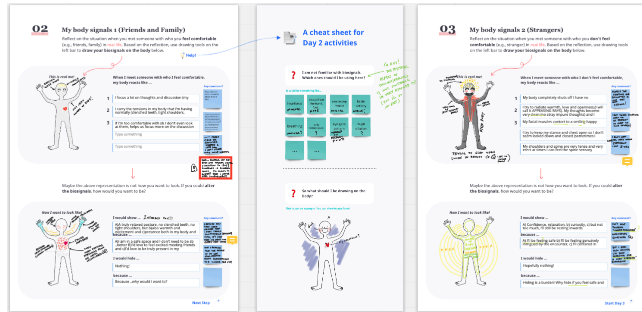


Figure 3: Screenshot of a filled out Day 2 Miro board booklet, as part of our context mapping.

3.1.2 Findings. 54 (M=26.2, SD=9.1) respondents (33m, 15f, 4 non-binary, 2 non-disclosed) across countries (x14) and ethnicities (x6) filled our survey. 48 respondents reported owning a VR device, 20 reported they use VR every day, 5 reported they use VR less than once a month, where the rest were in between. 45 respondents stated they have tried a specific social VR platform >10 times. The most used social VR platforms were: VRChat (81%), Rec Room (44%), AltspaceVR (37%), and Big Screen (37%). For each question (Table 1), we calculate the median (Md) and Inter-quartile Range (IQR). The top four questions exhibited good internal consistency (α = 0.79). Responses to the bottom three questions (where N indicates number of respondents) were contingent on whether a respondent had previously interacted with <friend, virtual friend, stranger>.

Three main findings emerged: first, users generally want to customize their avatar appearance, and do so in an idealized form **(F1)**. Second, currently recognizing others' emotions in social VR is still lacking, as seen by divided responses **(F2)**. Lastly, there was no clear consensus on revealing one's biosignals, except with regards to strangers, where this was not preferred **(F3)**.

3.2 Context mapping: understanding user - avatar relationships

Following our survey, we conducted context mapping sessions focused on social VR avatars and biosignals, using a two-step approach: sensitizing participants with a designed booklet (online), followed by interview sessions [99].

3.2.1 Procedure. **Sensitizing Booklet.** A sensitizing booklet was designed as a Miro[2] board[3] to help participants reflect on their (a) body reactions when interacting with someone in real life (b) current interaction methods when meeting people in social VR. The booklet was intended for use over three days (example in Figure 3)), each part taking ~10 min. to complete. Miro board links were sent beforehand along with consent and data privacy forms, where participants were requested to complete the booklet before the interview.

Interview. The interview aimed to extract further insights, where participants explained their booklet responses. Interviews lasted approximately one hour, and conducted in English over Zoom. Sessions were screen-recorded for later analysis.

3.2.2 Participants. Six (4m, 2f) of the survey respondents (M=27.3, SD=8.3), geographically spanning four countries and with diverse social VR experiences, were invited to the context mapping session. Selection criteria included: minimum 6 months of social VR experience (three had 3-5 years), usage of social VR at least once a week, and have interacted with friends and strangers in social VR. Participants were compensated with €15.

3.2.3 Analysis & Findings. We analyzed interview transcripts using a grounded theory approach [14, 95]. Responses were firstly segmented into high-level categories, and thereafter open codes were developed and validated by two independent coders, labeling them according to similarities in participants' responses. Since our goal was to yield concepts and themes, we do not calculate Inter-Rater Reliability [61]. Five main themes were uncovered:

T1: Expressing Emotion. Participants mentioned difficulties in adequately expressing their emotion. In such cases, they tried to express their emotions using hand gestures, voice chat, body movements, and emojis.

T2: Engagement and Comfort. When adopting the role of a host or manager of events, participants stated they frequently tried to check avatar reactions to make sure the audience is satisfied and engaged with the unfolding of the event. Engagement here was inferred from the avatar's body orientation, movements, emoji reactions, and messages sent.

T3: Presence of Self and Other. Participants mentioned that within social VR spaces, it was common for them to prove their presence in VR via any means (e.g., sending emoji), as it was not always apparent to them if they were present. Similarly, participants complained about not being able to check the presence of others, where they had to actively engage with an avatar.

T4: Biosignals for More Immersive Experiences. Participants mentioned that biosignals can make social VR spaces more immersive and exciting, where sharing feelings and emotions can

[2]http://miro.com/
[3]Copy of context-mapping board: https://miro.com/app/board/o9J_lSURcuI=/

help build more intimate relationships, or enrich current social VR experiences with more realism.

T5: Biosignals for Behavior Change. Participants mentioned that biosignals can play a role in improving current behavior, for example across medical applications or training settings. Relatedly, when biosignals are visualized for oneself, they could improve interoceptive awareness.

3.2.4 Design Direction. While the context mapping session highlighted several relevant factors for visualizing biosignals (T1-T5), it remained unclear how biosignals should be visualized for avoiding misinterpretations, distraction, and general design element obtrusiveness within social VR spaces. Given the large space of possible scenarios, we opted to focus on social VR entertainment, such as watching a movie at the cinema (e.g., Big Screen), or attending live music events (e.g., AltspaceVR concerts). This was chosen since prior work has shown potential for visualizing biosignals in entertainment settings (cf., [80, 89, 94]), where such settings have a more open and playful nature which can lower privacy concerns, and due to feasibility in later prototyping. Furthermore, we narrowed our scope to three common biosignals (HR, BR, Electrodermal Activity (EDA)), as these are well studied (cf., Feijt et al.'s [24] review), are expected to be familiar to participants, and allow visual design manifestation affordances.

3.3 Co-design: visualizing biosignals

To conceptualize suitable biosignal representations for social VR entertainment, we conducted an online co-design [84, 92] session: sensitizing participants with a designed booklet (online), followed by the co-design session.

3.3.1 Procedure. **Sensitizing Booklet.** A sensitizing booklet was designed as a Miro board[4], to help participants (a) reflect on their watching entertainment experiences with others in real life, and (b) learn about social VR. The booklet was intended to be used for ~30 min., and sent before the co-design session with consent and data privacy forms. The first part asked participants to reflect on their real-life experiences during entertainment activities with emphasis on bodily reactions. The second part consisted of watching videos covering social VR platforms within the entertainment sector[5].

Co-design Session. The co-design session aimed at visualizing three biosignals (HR, BR, EDA) between audience members during social VR entertainment (e.g., watching a musical performance). Session lasted approximately two hours, and conducted in English over Zoom with the Miro board[6] open. Sessions were screen-recorded for later analysis. Less familiar concepts (e.g., EDA) were explained during the session introduction. Participants were given an ideation template (Figure 4), that showed: a 3D avatar body model and a first-person perspective view. Participants were divided into three teams, each consisting of a student and industry professional, and sent into breakout rooms for three ideation rounds, and a constructive feedback session. Between the first and second ideation sessions, seven design considerations distilled from the survey (Sec 3.1) and

[4]Copy of co-design sensitizing booklet board: https://miro.com/app/board/o9J_lNuvwA4=/

[5]Video 1: https://youtu.be/jFJw312AHYE; Video 2: https://youtu.be/fA2cW2qgGgs; Video 3: https://youtu.be/SjPd9MCBh7Q

[6]Copy of co-design board: https://miro.com/app/board/o9J_lyvEjmg=/

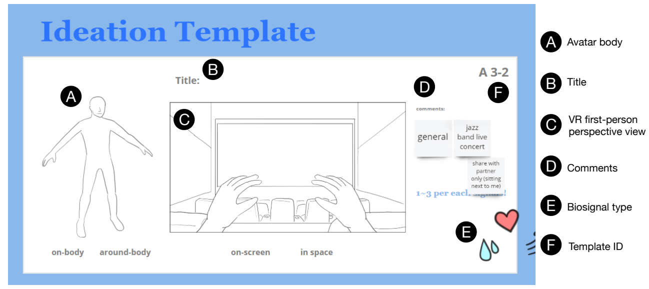


Figure 4: Example ideation template on a Miro board, designed to express one visualization idea per template.

context mapping themes (Sec 3.2) were provided to participants to consider and fulfill at least one. Three pertained to social VR (**R1**: Users find comfort when using the system; **R2:** The system allows users to express emotions; **R3:** The system allows users to check the presence of others) and four pertained to sharing and perceiving biosignals (**R4:** The system allows sharing feelings and emotions of others to add excitement; **R5:** The system allows sharing biosignals with others to enrich experiences; **R6:** The system secures an acceptable degree of privacy between users; **R7:** The system guarantees fairness when sharing data with others).

3.3.2 Participants. Six (4f, 2m) designers (*M*=29.5, *SD*=4.6) were recruited. Three were design master's students, two were industry UX professionals, and one freelance designer. Selection criteria included: owns a drawing tablet, confident in expressing ideas with drawings, and has attended public entertainment events (e.g., concert) with others. We did not require participants to have (social) VR experiences as this could limit designers' focus to current hardware capabilities. Nevertheless, one participant had extensive social VR experience (>30 visits), one tried a platform once, three were familiar with VR, and one had no VR experience. Participants were compensated with €25.

3.3.3 Analysis and Findings. Results from the session were analyzed following a similar approach to our context-mapping session (Sec 3.2.3). Two primary classifications were obtained from our analysis:

(a) Entertainment scenarios and interaction patterns. Analysis yielded patterns in how individuals behave across different entertainment scenarios. Based on interaction characteristics, entertainment activities were categorized into scenarios with three social engagement levels: **(S1)** Low **(S2)** Moderate **(S3)** High. S1 refers to entertainment activities in a quiet setting with fewer social exchanges, for example watching a film at the cinema (*P4: "...I was keeping chatting during the film to a minimum since I don't like disturbing plus I want to be immersed."*). Here, paying attention to the content is essential. S2 refers to entertainment activities that have moderate (or intermittent) social engagement, typically in a relaxed setting such as listening to music at a live jazz bar (*P3: "It was really good to see how other people enjoyed that moment."*). For this type, people enjoy the content as well as the mood and reactions of one's social surroundings. S3 refers to entertainment activities in a high social engagement setting, such as participating

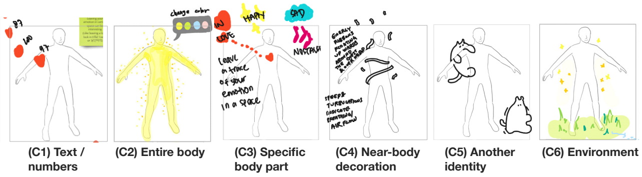


Figure 5: Selection of the resulting concept visualization sketches from the co-design session.

in open-air music festivals (*P4: "The music was loud and we were drinking too so we were chatting a lot loudly."*).

(b) Avatar biosignal visualizations. The co-design session resulted in six concepts (Figure 5) for visually expressing biosigals for social VR entertainment. C1 is a common representation (cf., [100]) that shows one's biosignal values through numerical or textual values near the avatar. C2 shows the avatar body as a whole can be deformed through color changes or body distortions. C3 is similar to C2, however applied to a specific body part (e.g., heart icon displayed on chest [15] or near the user's head [62]). C4 visualizes biosignals near the avatar as decoration, which is typically abstract (cf., [87]). C5 visualizes biosignals via a separate identity (cf., animated otters [56]). C6 visualizes biosignals on the environment or avatar surroundings (size, shape, or color) in social VR spaces (cf., [90, 94]).

3.3.4 Design Direction. Drawing on our design findings and earlier survey and context-mapping findings, we narrowed down our design space to entertainment activity S2 (Moderate Engagement). We specifically chose a music event setting of a live jazz bar, given earlier work that showed potential of biosignals to enhance such events [80, 89]. Given our scenario choice, we selected C3-C6 as suitable techniques to implement. In this setting, designing for peripheral attention [6, 60] plays an important role in ensuring users can enjoy the experience of being with others, without a constantly present obtrusive design element. Therefore C1 and C2 were omitted. Lastly, given that many participants were unfamiliar with EDA and found it difficult to design for it, and to ensure the subsequent study design can be tested in a controlled manner, we omitted this biosignal. The resulting biosignal (HR, BR) visualizations were then used in **Part 2**, where we investigated their perception in a virtual environment.

4 PART 2: EVALUATING BIOSIGNAL VISUALIZATIONS FOR SOCIAL VR ENTERTAINMENT

Based on our earlier findings (Part 1) and resulting design direction (Sec 3.3.4), we explore how visualizations C3-C6 applied to heart rate (HR) and breathing rate (BR) are perceived in a virtual jazz bar. Moreover, since we know from the human physiology literature that sensed biosignals can vary depending on users' arousal state (cf., physiological correlates of arousal [10] and the role of HR [103] and breathing [107]), we further considered signal rate (low, rest, high) as an additional variable of interest to test visualization effectiveness. While biosignal manifestations of physiological arousal may not always be equivalent, prior work suggests that there are numerous correlations between them [10]. Furthermore, this would provide an additional means to test the effectiveness of visualizations, given prior work that showed varied HR can lead to higher perceived avatar arousal [50]. Therefore, we investigate how our four visualizations (IV1), varied across HR and BR (IV2) and signal rate (IV3) influence perceived avatar arousal, participants' perceived distraction, and their overall visualization preferences. Below we describe our study design.

4.1 Study design

Our experiment is a 4 (IV1: Visualization: Skeuomorphic vs. Particles vs. Creature vs. Environment) x 2 (IV2: Biosignal Type: Heart Rate vs. Breathing Rate) x 3 (IV3: Signal Rate: Low vs. Rest vs. High) within-subjects design, tested in a controlled, virtual environment (Figure 6). This resulted in 24 different conditions, where conditions were counterbalanced according to a Latin Square design, with subsequent trials randomized. Gender of the observed companion avatar was also randomized to minimize VR gender bias effects (cf., [79]). We tested pairs of participants in an experiment session, as we expected this would heighten the experience of being socially present with a companion whose biosignals are visualized. However, the scenes in the experiment were experienced individually, where the avatars in each scene consisted of virtual agents.

Quantitative measures included the following dependent variables: (a) Perceived avatar arousal (b) Perceived visualization distraction (c) Overall visualization preference (d) IPQ Presence questionnaire [86]. Whereas all IVs (24 conditions) were applicable for measuring perceived avatar arousal, we did not include IV3 for perceived distraction and overall preference, as signal rate was not applicable for those trials. Rate levels were set to Rest in this case. Measures (a)-(b) took place within our custom VR jazz bar, where a Likert-scale panel was embedded in VR. This allows users to stay immersed in the VR experience [76]. We chose a 9-point scale here to allow greater rating sensitivity. Perceived avatar arousal scale (*"How high do you think the arousal of this avatar is?"*) ranged from very low (1) to very high (9) (Figure 9(b)), following the arousal dimension of the Self-Assessment Manikin scale [13]. Perceived visualization distraction (*"I find this visualization distracting."*) ranged from strongly disagree (1) to strongly agree (9). Overall visualization preference (*"My favorite visualization for showing <Heart Rate, Breathing> on a companion is:"*) took place outside of VR at the end, where four GIFs showing each visualization were presented as a forced-choice task (radio buttons). Igroup Presence Questionnaire (IPQ) uses a 7-point Likert scale, and used to assess the level of presence experienced in the virtual jazz bar. For qualitative measures, we ran a paired-participant semi-structured interview within-VR. This helped ensure participants' impressions are more directly related to what was observed, where they can easily refer to the biosignal visualizations during the group interview. The consensually audio-recorded interviews included asking participants about their overall experience, reflections on their responses, biosignal interpretations, added value and limitations, privacy issues, and other applications. Our study followed strict guidelines from our institute's ethics and data protection committee, including COVID-19 regulations.

(a) Backstage view. (b) View of paired-interview session.

Figure 6: The virtual jazz bar environment.

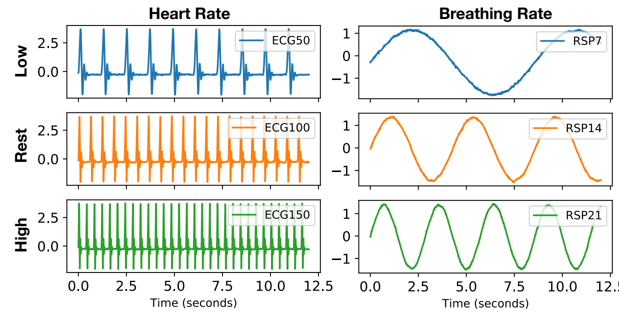


Figure 7: Generated biosignal plots across signal rates. Shows only 12s for image clarity.

4.2 Hardware and software setup

4.2.1 Technical setup. The VR jazz bar and visualizations were implemented in Unity[7]. Universal Render Pipeline was used for the Shader graph function to build the desired visualization effects. HTC Vive Pro Eye HMD was used for displaying the scenes. All 3D avatars and models were built with Blender[8]. Some of the environment 3D models were sourced from Sketchfab[9]. Rigged avatar animations were downloaded from Adobe Mixamo[10]. The foregoing tools helped ensure the environment and visualizations were aesthetically appealing.

4.2.2 Jazz bar environment. The jazz bar consists of a stage, tables, chairs, and extra ornaments (Figure 6). Within the jazz bar, other avatars with visualized biosignals are co-present alongside the participant's avatar. The user can see their companion, the audience, and the jazz band within their viewport. Western Saloon model from Sketchfab, alongside stage curtains and light models, worked as a rudimentary frame for environment creation. Point lights were used to create a dark and dim atmosphere, which served recreate a jazz bar atmosphere. Avatar models were built in Blender, where hairstyle and clothing color were varied for each avatar. All avatar models were auto-rigged using Mixamo. For music, "A Brand New Start" (genre: Jazz & Blues; Mood: Happy)[11] was selected to ensure a lively and positive virtual jazz bar experience.

4.2.3 Generating biosignals. Biosignal data with the desired duration, noise, and rate was artificially generated using Electrocardiogram (ECG) and respiration simulations within NeuroKit2 [59]. HR signals were generated using a 'Daubechies' wavelet that roughly approximates a single cardiac cycle, whereas respiratory signals are based on a trigonometric sine wave that roughly approximates a single respiratory cycle. While more complex simulations exist, we kept these simple given our focus on comparing visualizations in a uniform manner, and not on accurately modeling sensed biosignals. A total of six biosignals (High, Rest, and Low rates for HR and BR) were artificially generated (Figure 7), each for 24 seconds. This duration was deemed suitable for our purposes. We used a sampling rate of 1000 (default), with the following beats/breathes per minute (bpm) for each signal. For HR, we had high (150 bpm), rest (100), low (50). For BR, we had high (21), rest (14), low (7). These values are based on average human heart rates [3] and breathing patterns [7], respectively. However, these rates do span a range of human different activities, where for example a HR of 150 bpm is common after exercise, but not while sedentary.

4.2.4 Biosignal visualization design. We took two considerations into account when designing the final visualizations: (a) **Color:** early work has shown that bright colors tend to be associated with high valence and low arousal, while saturated colors tend to be more arousing than unsaturated colors [96]. However, recent work in affective visualization for VR [72] underscores the importance of the environment, where evidence indicates that color associations can change according to the context where colors are used [52]. Given little research on mappings between biosignals and color hue, and given our parameter space (visualization, signal type, rate), we defaulted on a familiar arousing (warm) red for HR, and a less arousing (cold) blue for BR [108, 109]. Brightness and saturation parameters were controlled as similarly as possible across the visualizations to minimize perceptual variance. Apart from Skeuomorphic designs which required shape (size) mappings, we varied only brightness (as emission intensity) for the rest, considering such visualizations may be used downstream with colorblind users (cf., [77]) (b) **Peripheral Attention:** Given our moderate social engagement setting (i.e., virtual jazz bar), we designed our visualizations with peripheral attention considerations (i.e., ambient awareness) [6, 60, 74] and aesthetics in mind. While we test these in a controlled setting, we expect that if these visualizations are used in social VR entertainment, they should be minimally attention demanding.

4.2.5 Biosignal visualization implementation. Our final visualizations (with resting rates) are shown in Figure 1, and overview and detailed videos in **Supplementary Material A & B**. They are publicly available on GitHub: **https://github.com/cwi-dis/CHI2022-AvatarBiosignalVisualizations**. Below we describe the visualizations, referring to the concepts in Figure 5.

1. Skeuomorphic: C3 adopts the familiar biosignal representation method ([15, 26, 43, 50, 62]) that follows a direct object to design mapping (i.e., skeuomorphic). 3D heart and breath bubble were built with Blender. HR and BR data were mapped to the size of the icons, and the pulse and rate of exhalation, respectively.

2. Particles: C4 represents biosignals through particles near the avatar. The amount, color, spiral shape, and frequency of particle emissions were controlled to transmit the intended biosignal data

[7]https://unity.com/
[8]https://www.blender.org/
[9]https://sketchfab.com/
[10]https://www.mixamo.com/
[11]From Youtube Audio library.

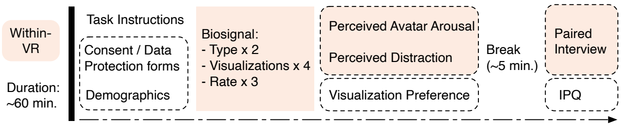


Figure 8: Our experiment procedure. Dotted outlines indicate required participant actions.

into particles, using Unity's Particle System. For HR, particles gave a burst when the HR reached its peak from one ECG cycle, where the number of particles for one burst was adjusted for different arousal levels. For BR, particle bundles were visualized after a sine graph of respiration, where start speed and particle amount were controlled so that the particle sum is maintained.

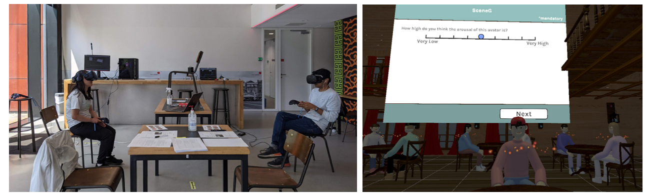
3. Creature: C5 is a third-party identity that represents the avatar's biosignals (cf., animated otters in [56]). A cat-like, moving creature either in red (HR) or blue (BR) was built in Blender. "Idle" and "Walk in Circle" animations brought the creature to life. For both biosignals, data was mapped to the emission intensity (flicker) of the creature's surface (material shader). Despite that the movement of the cat-like creature was not mapped to any biosignal parameters, we kept it with the considerations that in social VR entertainment a moving creature may be more suitable than an idle one.

4. Environment: C6 uses the surroundings for expressing the avatar biosignals ([90, 94]). As this can vary depending on the environment, we selected tables and chairs as a means to represent this, embedded where avatars are seated. A new material shader with an emission effect was applied to the rim of the table and the head of the chair, for both HR and BR.

4.3 Experiment setup and procedure

Our experiment procedure is shown in Figure 8, and lasted approximately one hour. Before the experiment, participants read and signed the data privacy and consent forms, and filled in demographic details. We gave an overview of the study and explained the study tasks, including a tutorial on how to navigate (via head movement) within VR, and selecting questionnaire responses. For the distraction question, participants were instructed to rate how distracting the visualization was from their experience of being in a virtual jazz bar and encountering a biosignal-augmented avatar. Participants were tested in pairs, and were seated facing each other in a spacious room each with their own headset and headphones (Figure 9(a)).

For the first (quantitative) part, a participant's avatar was seated in front of an (agent) companion avatar, where the Likert-scale questions were presented on a panel (Figure 9(b)). Participants were given an overview of the scene. They were then instructed to first observe their agent companion, the bar environment and band, and thereafter reflect on their experience. The music playing through the headphones ensured one participant's experience did not influence the other. Moreover, the tasks in this part were carried out individually, and did not require interaction between participants. Despite the nearby avatar audience, participants were asked to base their responses solely on the agent avatar. The VR questionnaire (Figure 9(b)) was sourced from VR Questionnaire



(a) (b)

Figure 9: (a) Study setup (b) Example within-VR panel showing perceived avatar arousal question.

Toolkit[12]. Participants entered responses with a button press on the Vive controller. After the questionnaire responses, they took a short break (~5 min.), and proceeded to the paired interview part. In this second (qualitative) part, two participant avatars and one experimenter avatar were sitting at the same table in the jazz bar. The paired participants in each session were only associates in real life. Here, the self-avatar gender representation matched the physical gender of each participant to avoid implicit biases [57]. The jazz band was still present but the music was switched off. Opposite to the band, four avatars showing the four visualizations were presented to help participants refer to them in real-time. Photon Unity Networking 2 (PUN 2) was used for networking between Unity files. Lastly, participants filled in the IPQ Presence questionnaire [86], and were compensated with €10.

4.3.1 Participants. 32 participants[13] (18f, 13m, 1 non-binary) aged 19-33 ($M = 26.7, SD = 3.6$) were recruited. Participants (23 undergraduate / graduate students) were recruited primarily (though not exclusively) from our institute, and spanned varied nationalities and backgrounds (> 5). 90.6% reported having tried HMD-based VR at least once, where only 21.8% reported having tried a social VR platform at least once. None reported visual (including testing for color blindness [44]), auditory or motor impairments.

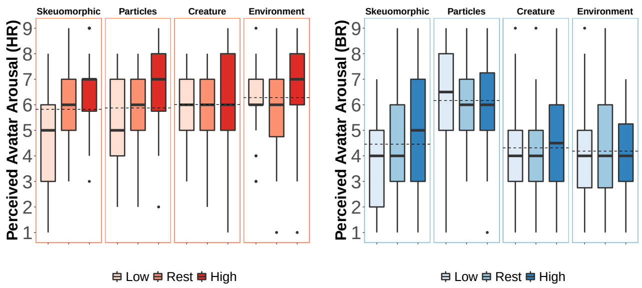
4.4 Results

We report our analysis of perceived avatar arousal ratings, perceived distraction ratings, visualization preferences, and IPQ scores. This is followed by our semi-structured interview qualitative findings. Shapiro-Wilk tests showed that arousal and distraction ratings, as well as IPQ scores, were not normally distributed ($p < 0.05$). Therefore, we ran non-parametric inferential statistical tests, and report medians (Md) and inter-quartile ranges (IQR) where necessary.

4.4.1 Perceived avatar arousal ratings. Perceived avatar arousal rating distributions for HR and BR are shown as boxplots in Figure 10(a) and Figure 10(b), respectively. Dashed lines show the mean for perceived avatar arousal per visualization.

We analyzed the combined effects of Signal, Visualization, and Rate by fitting a full linear mixed-effects model on our data. Since our data distribution is not normal, we applied the aligned rank transform prior to fitting [106]. Post-hoc contrast tests were performed using ART-C [23]. Analysis of deviance table is shown in

[12] https://github.com/MartinFk/VRQuestionnaireToolkit
[13] For effect size f=0.25 under $\alpha = 0.05$ and power (1-β) = 0.95, with 24 repeated measurements within factors, one would need minimum 12 participants.



(a) Heart rate (HR). (b) Breathing rate (BR).

Figure 10: Boxplots showing perceived avatar arousal ratings. Dashed line indicates mean score.

Factor	F	df	p
Signal	107.89	1	$< .001^{**}$
Visualization	13.42	3	$< .001^{**}$
Rate	12.52	2	$< .001^{**}$
Signal x Visualization	21.97	3	$< .001^{**}$
Signal x Rate	0.76	2	0.47
Visualization x Rate	2.42	6	$< 0.05^{*}$
Signal x Visualization x Rate	1.41	6	0.21

Table 2: Analysis of deviance on the full mixed-effects model using Aligned Rank Transformed data.

Table 2, where the model showed significance for all main effects: Signal, Visualization, and Rate. Moreover, we found significant interaction effects for Signal x Visualization and for Visualization x Rate.

Interactions analysis between Signal and Visualization revealed significant differences at 1% level for 15/26 level combinations. We report on six of these, as these are the most relevant (with the full list provided in **Supplementary Material C**). Contrasts comparisons between HR and BR showed significant differences for Skeuomorphic, Creature, and Environment. This indicates that visualizations do indeed have a dependency on the signal type. For contrasts within BR, we find significant differences between Particles on one hand, and Creature, Skeuomorphic, and Environment on the other. However, we do not find this for level interactions within HR. Interactions analysis (effect size range: [0.22-0.4]) between Visualization and Rate revealed significant differences for 14/66 level combinations. We report on the four most relevant. We find significant interaction effects at 1% level between Skeuomorphic (high) - Skeuomorphic (low), which lends credence to the suitability of the Skeuomorphic visualization in indicating arousal levels through rate. We also find significant differences between Skeuomorphic (low) - Particles (low), highlighting the differences across visualizations for low rates. Lastly, we find significant differences between Creature (high) - Particles (high), as well as Creature (rest) - Particles (rest) at 5% level. These highlight that even at the same rate, the visualizations Creature and Particles differed in their effects on perceived avatar arousal.

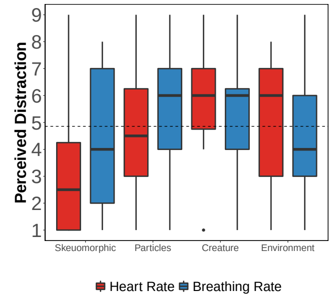


Figure 11: Boxplots showing perceived distraction ratings. Dashed line indicates mean score.

We further consider post-hoc differences among the perceived avatar arousal ratings. For HR-Skeuomorphic, post-hoc Bonferroni pairwise comparisons using Wilcoxon signed-rank tests revealed significant differences between low and rest ($Z = -3.27, p < 0.001, r = 0.33$), low and high ($Z = -3.94, p < 0.001, r = 0.4$), but not between rest and high ($p = 0.07$). For HR-Particles, post-hoc tests revealed significant differences between low and high ($Z = -3.33, p < 0.001, r = 0.34$), rest and high ($Z = -3.61, p < 0.001, r = 0.37$), but not between low and rest ($p = 0.09$). For Environment, post-hoc tests revealed significant differences only between low and high ($Z = -2.15, p < 0.05, r = 0.22$), rest and high ($Z = -2.45, p < 0.05, r = 0.25$), but not between low and rest ($p = 0.25$). These foregoing comparisons show that while for Skeuomorphic HR it is easier to infer arousal differences between low rates and any rate higher, the inverse applies for Particles and Environment, where differences between low and rest were not perceptually visible as between resting and higher rates. For BR, post-hoc comparisons for BR-Skeuomorphic revealed significant differences between low and rest ($Z = -2.73, p < 0.05, r = 0.28$), low and high ($Z = -3.39, p < 0.001, r = 0.35$), but not between rest and high ($p = 0.14$). This shows a similar effect as HR-Skeuomorphic, where it appears to be easier to infer arousal differences between low rates and higher, but not between resting and high rates.

4.4.2 Perceived distraction ratings. Perceived distraction rating distributions for HR and BR are shown as boxplots in Figure 11. Dashed line shows the mean of perceived distraction scores across visualizations.

We analyzed the combined effects of Signal and Visualization by fitting a full linear mixed-effects model on our data. We followed a similar process to Sec 4.4.1. Analysis of deviance showed a significant main effect for Visualization ($F = 5.53, df = 3, p < 0.05$) and Signal x Visualization ($F = 3.77, df = 3, p < 0.05$), but not for Signal ($F = 0.28, df = 1, p = 0.59$). Interaction analysis (effect size range: [0.23-0.31]) between Signal and Visualization revealed significant differences at 1% and 5% level for 4/28 level combinations. Two relevant interaction effects are worth noting (with the full list provided in **Supplementary Material C**): HR (Creature) - HR (Skeuomorphic) ($p < 0.001$), and HR (Skeuomorphic) - HR (Environment) ($p < 0.05$). This shows that even when considering interaction effects, HR-Skeuomorphic seems to be overall less distracting than all but Particles.

Post-hoc Bonferroni pairwise comparisons using Wilcoxon signed-rank tests revealed significant differences between HR-Skeuomorphic and HR-Creature ($Z = 3.48, p < 0.001, r = 0.31$), HR-Skeuomorphic and HR-Environment ($Z = -3.12, p < 0.05, r = 0.28$), and HR-Particles and HR-Creature ($Z = -2.59, p < 0.05, r = 0.23$). However, no other significant effects were found. Interestingly, while HR-Skeuomorphic seems to be the least distracting visualization, it was not statistically less distracting than HR-Particles.

4.4.3 Overall visualization preference. Participants were asked about their favorite visualization preferences. For HR, Skeuomorphic (84.4%) was the most preferred, followed by Creature (9.4%), Particles (3.1%), and Environment (3.1%). For BR, Skeuomorphic (37.5%) and Environment (34.4%) were the most preferable, followed by Particles (18.8%) and Creature (9.4%).

4.4.4 IPQ. IPQ scores were as follows: G - sense of being there ($Md = 6, IQR = 1$), SP - spatial presence ($Md = 5, IQR = 2$), INV - involvement ($Md = 4.25, IQR = 3$), REAL - experienced realism ($Md = 3.75, IQR = 3$).

4.5 Interview analysis

We follow a similar analysis procedure to Sec 3.2.3, which resulted in four main themes. Each theme is discussed below, where 32 participants are labeled P1-P32. Participant counts > 5 are shown numerically.

4.5.1 Biosignal visualization reflections. **Skeuomorphic:** Several participants (9) found this visualization to be intuitive and familiar. It was readily interpretable due to speed and size changes, for both biosignals. It was also found to be minimally distracting by allowing more focus on an avatar (*P22: "...if I'm in front of someone, then I want to focus on a conversation. So that was the most direct one and takes me less effort to understand."*).

Particles: While few participants (P10,P11) found the particles gave an overall atmospheric feeling, others (8) found it confusing (*P12: "Particle ones are cool, but unclear for me...hard to notice its speed change. And it was surrounding the person, so it will be a little bit distracting").* One participant however mentioned its relevance for a concert-like setting (*P28: "I could totally see...in the concert, it's glowing up."*).

Creature: Several participants (10) mentioned that the creatures were too cute and do not represent the signals well, where among those (P10,P16,P24,P26) also mentioned their distracting nature. Furthermore, many (9) regarded the creatures as separate identities due to their distance from and movements around the avatar. For HR specifically, one participant mentioned that the ambiguity of the creature was favorable *(P28: "I liked the character showing the heartbeat because it's not really directly related to me.").*

Environment: Some participants (5) found that the environment change visualization was most suitable for showing the atmospheric mood. The peripheral aspect of attending to it was highlighted *(P26: "Because you can look at it and not look at it both. So that was really good for me because I was comparing the same experience with what happens in real life".)* This lends support to our approach of designing for peripheral attention.

4.5.2 Biosignal visualization in social VR. Three sub-themes emerged that pertain to perceiving biosignals in social VR:

Understanding Emotions and Moods of People and Spaces. Some participants (8) mentioned that biosignals would only be helpful if they help them understand others' emotion states (P12: "If these data cannot let me understand their emotion, then it will just be extra information...but it's interesting."). Additionally, visualized biosignals can help people see the general vibe or mood of a virtual space (*P11: "...if you step into the room, you don't know anybody, but you want to know what is happening, right?"*), or create stronger bonds with others (*P13: "...we really need this to have more bonding between our interaction."*.

Connecting with Others and Immersion. Participants found biosignals as a means to better connect with others. Participants (P1,P2) stated they would be more curious about a strangers' biosignals than someone they know (*P1: "...more interesting to look at a person's biosignals who I met for the first time."*). Few (P3,P8,P9) mentioned that such biosignals could be used as an icebreaker (*P3: "I see your little animal [Creature], where did you get it?"*). Others mentioned they only care about their friends' or family members' biosignals. For some (P1,P3,P17), biosignal visualizations provided a feeling that who they spoke with is in fact a real person (*P16: "I feel like I'm in a video game...but if you show a heartbeat or breathing...I feel like more connected."*). Others (P1,P32) suggested that biosignal visualizations in a public, crowded setting can contribute to creating a unique atmosphere (*P31: "If we are at a concert, if I can see everybody's biosignals, it could contribute to the atmosphere."*). Lastly, the benefits of customization was mentioned (*P3: "If a person personalizes their own way of visualizing their biosignals, I think the space can be more colorful."*).

Biosignals beyond a Jazz Bar. One participant stated explicitly that perceiving biosignals would be more beneficial in safety-critical settings, or to aid self-reflection (*P11: "...hesitant to talk to the therapist..if it triggers you, then you can know from the fluctuation."*). Other use cases included biosignals as a (social) rating of quality (*P32: "...in restaurants...better arousal data means that the food is good."*), or as a performance improvement metric (*P7: "If a band is performing, the manager can get information from the VR headset."*).

4.5.3 Biosignal (mis-)interpretation. While our quantitative analysis shows that overall avatar arousal levels can be differentiated, some found this confusing. For several participants (11), the visualization color influenced avatar arousal interpretation, where they often linked the color red to high arousal, and blue with calming and low arousal (*P28:"...every breath felt more calming while every red color felt more arousing."*). While this was part of our design approach (Sec 4.2.4) where participants were explicitly informed, it nevertheless led to misinterpretation. Occasionally, participants (P7,P14,P18) took the jazz band music into account when they rated arousal levels, despite being told there is no association. Several (8) found the Creature confusing given their motion parameters, which were not mapped (*P23: "...for the creature, it was confusing when the creature started to move."*). Others found BR to be difficult to interpret due to its slower peak cycles (*P20: "...breathing could be slower than the heart rate. It could be heavy, but at a slower rate, both could potentially indicate higher arousal."*). In some cases however, biosignals could remove barriers of misinterpreting others or providing additional social cues (*P15: "...a good substitute for body language....we'll see some things that you can't normally seen in non-VR setting. Breathing - you can tell, but the heartbeat, not necessarily, so that's cool."*).

4.5.4 Privacy concerns in sharing and perceiving biosignals. Whereas some participants did not have privacy concerns (P2,P8,P9,P32), many (9) found sharing biosignals within social VR concerning, whereas others (13) highlighted the importance of context. Some (8) mentioned that since HR and BR is already visible, sharing is acceptable. The acceptable degrees of sharing biosignals varied according to setting (e.g., conference, cinema), or their relationship with an avatar (*P11: "I am okay with sharing my data with that person who I know. But not everyone in the room."*). Furthermore, designs can be acceptable if they do not show exact numerical values. Relatedly, some (6) wanted to avoid too much transparency by revealing their innermost feelings. To this end, one suggested data obfuscation strategies (*P22: "Maybe I can show 80 percent of real data and the other 20 are fake data."*). Despite such concerns, others (*P11, P14*) wanted to see other peoples' biosignals even if hiding their own (*P14: "I don't know if I want them to know what I'm actually feeling. But I would love to know what they are feeling."*).

5 GENERAL DISCUSSION

5.1 Limitations and future work

First, given our controlled study, we restricted ourselves to simulated biosignal feedback, where we do not consider live biosensing nor more complex heart rate (HR) [64] and breathing rate (BR) parameters [27, 75, 81]. While our scope was to firstly identify suitable and interpretable visualizations for social VR entertainment, this required simplifying parameter choices, where mapping to real-time sensed biosignal data and measuring physiological reactions (e.g., pupil dilation) is a natural progression towards future work. Relatedly, we do not address cases of a mismatch between the perceived avatar biosignals and the true arousal status of a user embodying that avatar. Similarly, while we do not consider congruence between a person's emotional state and their avatar biosignals, these aspects can increase future ecological validity. Second, we found Skeuomorphic designs were generally most preferred, which raises the question of whether these are due to mere exposure effects [110] or mapping familiarity. While this would ideally be tested through a longitudinal study to tease out familiarity and novelty effects, our participant sample size and novelty of biosignal visualizations should not undermine participant responses.

Third, we focused only on visual representations. While prior work has shown for example that the sound of a heartbeat can serve as an expressive biosignal cue [19] and can elicit empathy [105], such cues can be obtrusive for social VR experiences, especially in an environment with music. Nevertheless, we aim to later explore such multimodal feedback (e.g., affective thermal stimuli [22]) as potential biosignal visualizations. Fourth, our perceived distraction measures should be interpreted cautiously given our controlled scenario, where attentional demands and how distractions from real-world avatar interactions unfold need to be investigated further. Fifth, while we focused on HR and BR, subsequent work should consider other biosignals (e.g., EEG) for wider applicability, and combinations of biosignals visualized simultaneously. Lastly, while we considered the role of color perception (cf., [96]) and use of brightness as a more universal design element, further testing is needed to mitigate any biases that emerge in affective interpretation [8, 72], and ensure accessible designs for color-impaired individuals.

5.2 Towards expressive biosignal visualizations in social VR entertainment

One goal of this work **Part 1** was to understand current user perceptions towards avatars and expressive biosignals in social VR **(RQ1a)**, and how they are visualized for entertainment spaces **(RQ1b)**. Our research resulted in key findings related to customizing avatars, limits in expressing emotion, indicating presence, engagement, comfort, immersion, and privacy concerns. Based on these and our controlled study, we find that virtual avatars can be augmented with expressive biosignals to allow richer forms of understanding virtual people and spaces (cf., [30, 40]), can reconfigure and enhance connections with others (e.g., through authentic communication [56]), and have the capacity to make social VR more immersive and exciting [94]. However, the choice of biosignal design is paramount to avoid misinterpretations, which echoes similar findings from Howell et al. [43] who caution about the often inherent ambiguities in biosignal cues. Given our study design using synthetic biosignals, we cannot currently distill how our visualizations are perceived during natural (e.g,. conversational) social VR interactions (cf., immersive concerts [9]), which is reflected in our moderate Realism and Involvement IPQ scores (Sec 4.4.4). Nevertheless, our work provides the foundations for deploying such visualizations in the social VR wild, and provides opportunities to further explore the role of biosignals in physiological synchrony and social connectedness.

Furthermore, the type of relation towards an avatar (friend, virtual friend, stranger), and type of entertainment scenario (low, moderate, high engagement), impacts not only how biosignal visualizations are perceived, but also their suitability. For example, visualizing numerical HR values may not be appropriate in a moderate socially engaging setting such as jazz bar, but can be for medical settings (cf., Sec 4.5.2). This furthermore relates to the recurring finding (cf., sharing HR [53, 90] and breathing [27]) of expressed privacy concerns over sharing and perceiving biosignals, and responsible use in general. Here, it is paramount for users that such visualizations do not always reveal detailed biosignal data with strangers. While we took considerations of responsible technology embodiment into account [4] and situated our work in social VR entertainment spaces, further ahead it may necessitate a more contextual approach towards biosignal privacy (cf., [70]).

5.3 Biosignal visualization effectiveness in a Social VR entertainment setting

Within our virtual jazz bar scenario, we investigated the effects of different visualizations (**RQ2**) of HR and BR on perceived arousal, distraction, and preferences. For perceived avatar arousal, we found that a Skeuomorphic design allowed differentiable inferences of avatar arousal for both biosignals, however with easier arousal inference between low rates and higher. Being able to infer such differences supports Li et al.'s [50] findings, who found that varying HR can lead to higher perceived avatar arousal. We also find that visualizations do indeed depend on the signal type. This has downstream implications should such biosignal visualizations be measured precisely using biosensors, where one would not have clear-cut, constant signal rates, possibly resulting in increased interpretability issues; so-called "ambiguity of observation" [43]. This may require amplifying the visualization so that even smaller value fluctuations are visually exaggerated. This becomes important if one chooses more subtle indicators to visualize biosignals (cf., realistic blood flow animations [63]), where such indicators may not be discernible during social VR interactions. For perceived distraction, we found that Skeuomorphic was the least distracting for HR, but not statistically less distracting than Particles, even when considering interactions. By contrast for BR, the visualization type did not statistically influence distraction ratings, suggesting BR designs were generally distracting away ($Md = 4 - 6$) from the bar experience and companion avatar.

Given our entertainment setting, a recurring theme was on understanding the emotions and moods of people (avatars) versus spaces. We expected that visualizations more geared for peripheral attention [6, 60, 74] (Creature and Environment) would be overall more suitable for social settings, following Gradl et al.'s [33] findings that a screen pulse overlay is most suitable (albeit for interoceptive awareness). We instead found Skeuomorphic designs to be the least distracting (Sec 4.4.2) for HR, highlighting tensions between interpretability and reported attentional demands. This does however support Ceenu & Hassib's [30] findings, who found that an 'aura' avatar visualization that was always visible to be the most preferred. By contrast, BR visualizations did not significantly differ with respect to perceived distraction, where overall preferences showed that Skeuomorphic designs were similarly preferred as Environment (Sec 4.4.3). This shows that the biosignal type and its rate can influence both interpretability and distraction, irrespective of its visual representation.

5.4 Design considerations for social VR entertainment

More interpretable, less distracting. We find that skeuomorphic designs, due to their familiarity and interpretability, are a preferred means of visualizing biosignals since they are perceived to be less distracting. However, for understanding the atmosphere or ambience of a virtual space, other visualizations such as environment change may be more suitable (e.g., virtual emotion isles [88]). Furthermore, for Creature, we found participants felt confused when interpreting multiple design elements, which suggests that for maximum effectiveness, either all design elements should have a clear mapping to a biosignal, or consider only few parameters.

More visualization customization, more ambiguous interpretations. It became evident that individuals would prefer to customize their own biosignal visualization (Sec 4.5.2). However, without a standardized set of visualizations that are familiar to users, this can come at the cost of ambiguous social interpretation [43, 53], obtrusiveness, and even trustworthiness [65]. Therefore, the types of interactions and attitudes a social VR space with multiple avatar biosignal visualizations affords, remains open.

Perceiving, but not sharing biosignals. Despite that participants valued perceiving biosignals, many expressed privacy concerns, from who these biosignals are being shared with, to which abstraction level the data sits. This echoes previous findings from Hassib et al. [40], where people reported enjoying perceiving others' biosignals, but not themselves sharing (Sec 4.5.4). This leaves it open to what extent such signals would be shared if social VR users have access to the right privacy-centric visualizations, and under which entertainment scenario.

Biosignal animations can falsely indicate availability status. We find that biosignals can play a role as avatar online status indicators (cf., awareness displays [20]). This can provide another means for "idle" users to indicate their presence to others in a social virtual space (Sec 3.2.3, **T3**), or even allow verifying humanness (Sec 4.5.2). However, this can also provide a new means to mislead others [16] in facilitating wasted interactions. Given this, one would need to consider freezing the biosignal, since the animations can provide the incorrect social cue at times.

6 CONCLUSION

This work aimed at addressing how users perceive biosignals in social VR entertainment, and how biosignal visualizations can be sensibly integrated into avatars. Based on several studies, we arrived at four biosignal visualizations, and explored in a controlled study their effects on perceived avatar arousal, user distraction, and overall preferences. Our findings show that (a) skeuomorphic visualizations for both HR and BR allowed differentiable inferences of arousal (b) skeuomorphic and particles were the least distracting visualization for HR, whereas no statistical differences in distraction were found for BR visualizations (c) participants' perceived suitability of a biosignal representation often depends on the type of relation towards an avatar, type of entertainment, and whether the purpose is for understanding emotions of an avatar or the emotion/mood of a space. Our work provides insights on how user perceive biosignals in social VR, four empirically validated biosignal visualizations (**https://github.com/cwi-dis/CHI2022-AvatarBiosignalVisualizations**) for HR and BR, and design considerations and insights that can support future researchers and practitioners in creating more effective avatar biosignal visualizations for social VR entertainment.

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