# My Heart Will Go On: Implicitly Increasing Social Connectedness By Visualizing Asynchronous Players' Heartbeats in VR Games

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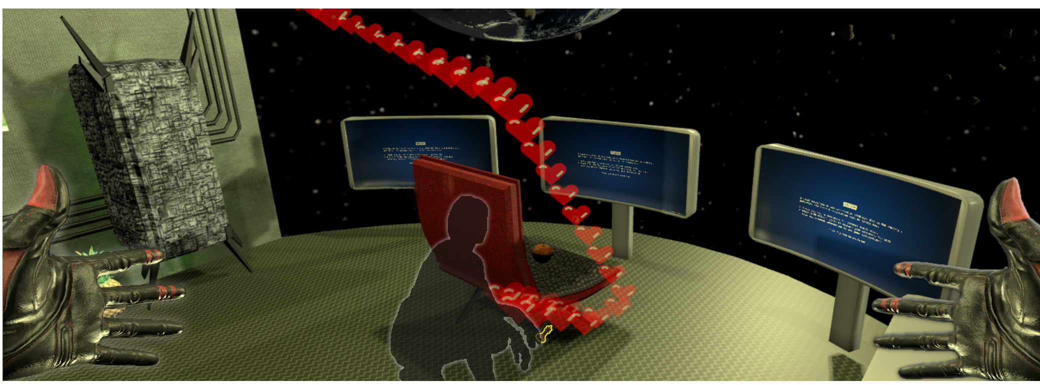

Fig. 1. A user sees an asynchronous player's single heartbeat visualization as pulsating heart icons. The visualization is temporally and spatially embedded according to the player's movement through virtual reality (VR). We added a person's outline to communicate the relations. The accumulating heart icons indicate that the player spent longer at that spot.

Social games benefit from social connectedness between players because it improves the gaming experience and increases enjoyment. In virtual reality (VR), various approaches, such as avatars, are developed for multi-player games to increase social connectedness. However, these approaches are lacking in single-player games. To increase social connectedness in such games, our work explores the visualization of physiological data from asynchronous players, i.e., electrocardiogram (ECG). We identified two visualization dimensions, the NUMBER OF PLAYERS, and the VISUALIZATION STYLE, after a design workshop with experts (N=4) and explored them in a single-user virtual escape room game. We spatially and temporally integrated the visualizations and compared two times two visualizations against a baseline condition without visualization in a within-subject lab study (N=34). All but one visualization significantly increased participants' feelings of social connectedness. Heart

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icons triggered the strongest feeling of connectedness, understanding, and perceived support in playing the game.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; **Virtual reality**.

Additional Key Words and Phrases: social VR, escape room, single player, physiological data, asynchronous, VR game, shared biodata, visualization, heartbeat

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## 1 INTRODUCTION

Social virtual reality (VR) games, such as OrbusVR[1], VRchat[2] or Rec Room[3], have become increasingly popular in recent years. One of the driving success factors in social games [5, 87] is the feeling of social connectedness; the indicator of how users experience social relationships and dynamics within a shared environment [48, 51]. Enabling users to feel socially connected increases their level of immersion [18], enjoyment [67], and improves the gaming experience [59, 66]. To support social connectedness, multi-user VRs often use features that highlight the presence of others, such as avatars[4] with facial expressions or body postures [42, 94, 98, 101]. However, single-player VR games often lack the presence of others and the advantages it provides.

A possible way to provide social experiences in single-player scenarios is to incorporate implicit social cues and traces about others' previous activities into the user's activities [23, 34, 54, 63]. By this, single-player scenarios could indicate what other single-players have done without altering the game character in addition to high scores or other outside-the-game scenario features. Alternatively, single-players could also share the same space and turn single-player games into asynchronous game environments in which players are present at different times [84]. In both ways, this approach fosters social connectedness asynchronously and creates "shared awareness" spaces [23, 35]. As concrete examples for this, game designers have integrated navigation, movement, or activity traces such as other users' footsteps or desire paths in single and multi-player games[5][6][7]. However, such traces typically represent strictly performance-oriented information such as actions and scores of other players. As such, these traces lack information about how other players felt during their activity, which is fundamental information to build social connections [32, 74]. A promising research trend in this context is including physiological data as socio-emotional cues [63, 84]. Physiological data, such as heart rate, breathing rate, or skin conductance, reflect our affective states [22, 100, 104] and, when shared with others, can similarly evoke emotions in others [32, 39]. Yet, physiological data as social cues has only been researched as additional information to a user's avatar [74, 104] or as part of a gaming menu in synchronous social situations [31]. Providing physiological data without the other user being present challenges how it should be integrated to be understandable and meaningful [28, 41, 103].

Our work adds to the increasing research on social VRs by exploring asynchronously shared and in the VR embedded physiological data to increase social connectedness. To this end, we

[1]https://orbusvr.com/, last accessed Feb. 6th 2023
[2]https://hello.vrchat.com/, last accessed Feb. 6th, 2023
[3]https://recroom.com/, last accessed Feb. 6th, 2023
[4]Avatars are virtual user representations.
[5]https://horizon.fandom.com/wiki/Horizon_Zero_Dawn, last accessed Feb. 13th, 2023
[6]https://www.nomanssky.com/beyond-update/?cli_action=1635529112.09, last accessed Feb. 13th, 2023
[7]https://www.epicgames.com/store/p/death-stranding, last accessed Feb. 13th, 2023

conducted an iterative design and study approach, including a design workshop with four experts to discuss different types of physiological data in the first step. The workshop results suggested exploring heartbeat data further. Furthermore, it resulted in the recommendation to compare the effect of single- versus multi-heartbeat visualizations (NUMBER OF PLAYERS) in combination with heartbeat values displayed through scientific electrocardiograms (ECG) versus symbolic heartbeat visualizations in the form of heart icons (VISUALIZATION STYLE). For this comparison, we created an escape room game (see Figure 1), including five different stories and five test conditions: four different visualizations, two different numbers of players, two different visualization styles, and one baseline condition without visualization. We chose this type of game because it is a collaborative game [90, 106] that is still often played as a single-player game when played in VR or online. We gathered real-player ECG data in a pre-study (N=4) to create the visualizations in this game. Finally, we conducted a within-subject study (N=34) testing the visualizations' effect.

*Contribution.* Our results show that asynchronously sharing others' heartbeats and embedding them in the game significantly increases social connectedness. Additionally, embedding the data by contextualizing it temporally and spatially provides navigation guidance and implicitly fosters an understanding of asynchronous players' activities. Thus, such data visualizations support players in making meaningful social connections without needing direct or verbal communication. However, displaying multiple players' physiological data also distracts users from primary tasks such as escaping the room. The symbolic data visualizations (heart icons) triggered a greater feeling of social and emotional connectedness and understanding for others' activities and provided greater support in the gameplay than the ECG visualizations. This work contributes to implicitly fostering the social connection between asynchronous players with spatially and temporally embedded physiological player data visualizations, including three design recommendations for visualizing and sharing heartbeats to foster social connectedness asynchronously. We emphasize research opportunities for future work on single and multi-user VR and other reality contexts. Our findings are relevant for designers and researchers who aim to enrich single-user VR experiences with embedded social cues.

## 2 RELATED WORK

Below, we give an overview of 1) current VR research on social connectedness followed by 2) an introduction to physiological data in games. Further, we 3) introduce heartbeat visualizations in VR design as our design workshop identified this physiological data as the most promising. We conclude with a 4) summary of the current research gap that we approached in our work.

### 2.1 Designing for Social Connectedness in VR Contexts

Designing for social connectedness can enrich the gaming experience [59, 66] and contribute to users' well-being [79]. At the same time, social connectedness can also cause negative experiences through the toxic or harmful behavior of others [9, 11, 63] or by users feeling more lonely through having developed the wrong type of social connectedness [64]. Previous work has increased social connectedness through, for example, avatars as virtual user representations, including non-verbal communication cues [93], body language [95], shared bio data [61, 74] and facial expressions [101]). Similarly, VR game research explored co-located and asymmetric gaming scenarios [3, 52, 111] or collaborative virtual games [32]. [32], for example, fostered social connectedness among two players by sharing their heart rates with each other. In asynchronous VR contexts, prior work observed increased understanding of others' activities and social connectedness due to changes made in the environment through user manipulation [23, 55, 65] or explored asynchronously shared messages [11]. Asynchronous usage of social VRs is increasingly enabled for, for example, long-term VRs, such as shared learning [27, 85], work [23, 47], or health education [108, 109] contexts. Yet, identifying approaches to fostering social connectedness in asynchronous VRs is an ongoing research challenge [55].

### 2.2 Physiological Data as Meaningful Game Feature

Sharing physiological data between users strengthens social connectedness [100, 104] and understanding about one's own [30, 63] and others' emotions [36, 74, 76]. Consequently, prior work has researched physiological data to alter and intensify gaming experiences [36]. D'Souza et al. [36] presents a hat displaying heart rate, skin conductance, and skin temperature measurements to co-players, which participants used to make assumptions about the player's playing strategy or affective state. However, one of the big challenges in sharing meaningful physiological data is that they require additional information to mitigate their ambiguity [28, 81]. Multi-player VR and video games are the most common application contexts for shared physiological data because it connects co-players by informing them about each others' state [84]. Consequently, such data can intensify the gaming experience by making it more meaningful and supporting players to collaborate or compete [19, 30, 32, 88]. A recent literature survey by Moge et al. [84] (2020-2021) on shared physiological data applications revealed that the topic has not yet been explored in asynchronous VR contexts. The lack of the other user's synchronous presence makes integrating physiological data more complex [28] and requires researching alternative approaches to embed it into VR. The knowledge gap also makes it unclear what impact the integration of such asynchronously shared data has on the gaming experience when embedded into the game environment.

Considering the knowledge gap and the lack of approaches for fostering social connectedness asynchronously with physiological data in single-player games, this work is guided by **two questions**: i) How can we design in-game embedded physiological data cues to increase social connectedness asynchronously? ii) How do such data and visualizations influence the gaming experience?

### 2.3 Heartbeat Visualizations in VR

Among the different types of physiological data, electrocardiogram (ECG) is one of the most researched and accurate markers for the inter-dependency of arousal and physical activation [17, 92]. Nonetheless, the data needs to be meaningfully, clearly visualized, and presented to be understandable and to trigger the effect designers intend. George and Hassib [43], for example, suggests a color-coded glow coming from the avatar body or an arrow above the avatar's head to trigger the feeling of connectedness among users. Lee et al. [74] present four visualizations to enrich the avatar with depictions of the user's arousal. Their results identify skeuomorphic (a graphical representation of familiar real-world concepts [40]) visualizations and particles as the least disrupting and show that these are also well-suited to indicate arousal. Other research has explored heartbeat visualizations by, for example, altering the pulsation speed [31] and a variety of shapes, such as shape-shifting fur [10], bar charts [46], pulsing overlays and cube grids [44]. Similarly, Javaid and Khan [62] researched the form of a pulsating, biological heart. Except for Grioui and Blascheck [46], each of these projects presents heartbeat data as a dynamic, changing visualization, sometimes close to the natural heart's appearance [62] and sometimes in very abstracted shapes [10, 44]. Most of the presented work provides heartbeat visualization as an augmentation or extension of a virtual avatar and explores them in shared, synchronous situations.

### 2.4 Summary

Physiological data, particularly heartbeat, is an established means to increase users' social connectedness and awareness. VR games are one of the main application areas for social and physiological data, but prior work highlighted a knowledge gap in asynchronous social VR scenarios. We explore the effect of asynchronous players' physiological data on social connectedness, understanding of others' activities, and gaming experience in a self-developed virtual escape room game. We hypothesize:

**H1** Displaying real asynchronous players' ECG data that is temporally and spatially integrated into the VR game scene improves players' (H1a) social connectedness, (H1b) gaming experience, and (H1c) understanding of other players' activities compared to having no data visualization.

To this end, we leverage findings from prior work and an expert design workshop to create heartbeat visualizations.

## 3 GAME CHOICE AND DEVELOPMENT

We developed a single-player escape room game, in which the asynchronously shared data could strengthen the collaborative or competitive game character.

### 3.1 Motivation to Select a Virtual Escape Room Game

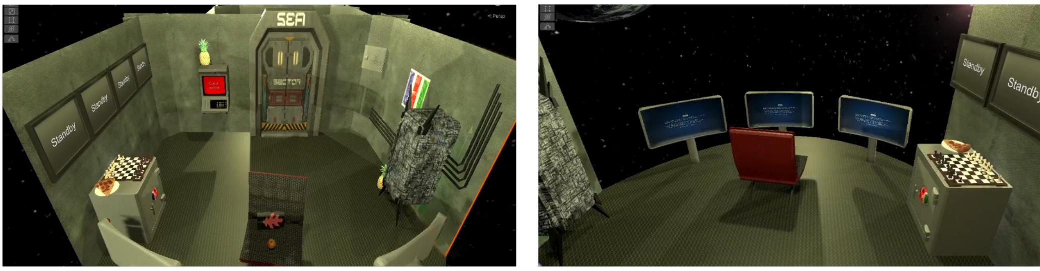
Escape rooms are collaborative, serious games that can be played in physical and virtual reality [37, 70, 90, 106]. Players are introduced to a story evolving around the gaming scenario, which generally ends with the players' mission to exit the room[8]. To achieve this, they need to find and solve a sequence of riddles. If players get stuck, either the game moderator provides hints verbally or they receive hint cards. In contrast, online or virtual escape rooms are often played in single-player mode (for example, Viking Escape[9] or Escape Academy[10]), lacking the social gaming experience and the serious game character regarding learning [80] to communicate, divide task or coordinate [106]. This gap between virtual and physical escape room games motivated us to develop an escape room game for the context of our study as a representative single-user VR game. We imagine our findings could inform game designers about alternative game mechanics to keep the social experience even during single-player modes.

### 3.2 Game Environment and Mechanics

The escape room developed for this study represented an abandoned space station, which we implemented in Unity version 2021.3.4f1. The escape room comprises various screens, a chair, a computer, a fridge, and a safe (see Figure 2). We also included objects attached to the walls, food leftovers, and a chess game. The room is kept open to one side to show the outside and to emphasize the feeling of being in space. Compared to other escape room games, we limited our game to one room only to reduce the playing time.

As game mechanics, we developed riddles informed by common riddle types according to online blogs[11]. These include, for example, matching pictures with objects in the environment, moving or counting objects of a type, etc. In our scenario, we applied the riddle types by, for example, matching the color sequence displayed on the poster with the color of the screens or counting the number of pineapples distributed in the room to get to the next clue hidden in the safe. Please refer to our supplementary video for visual examples and the supplementary material for more details about the riddles, hints, and stories.

[8] https://theescapegame.com/blog/what-is-an-escape-room/, last accessed Feb. 13th, 2023
[9] https://store.steampowered.com/app/554700/Viking_Escape/, last accessed Feb. 13th, 2023
[10] https://store.steampowered.com/app/1812090/Escape_Academy/, last accessed Feb. 13th, 2023
[11] https://escaperoomtips.com/design/escape-room-puzzle-ideas, https://elevenpuzzles.com/blog/popular-puzzle-types/, last accessed Feb. 13th, 2023




(a) (b)

Fig. 2. Our VR Escape Room: a) from a bird's eye view outside the room and b) from a player's perspective inside the room.

## 4 DESIGN WORKSHOP: IDENTIFYING HEARTBEAT AS PHYSIOLOGICAL DATA VISUALIZATIONS

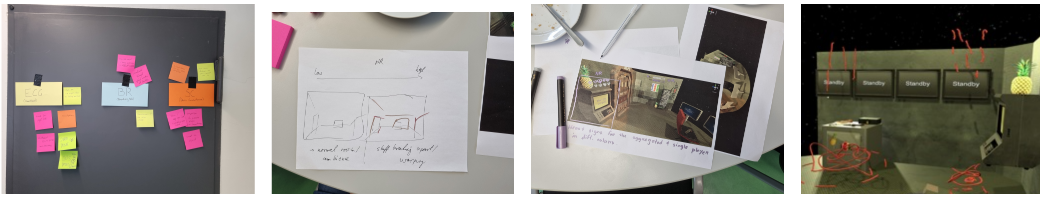
We conducted a design workshop with four experts to identify i) the information relevant to provide to players, ii) the physiological data to be measured, and iii) potential visualization designs. Such a design workshop supports generating diverse ideas for the design and embedding of the visualization while discussing the potential and limitations of the suggestions between the experts. We did not conduct the workshop with actual players, because, at this point, we needed insights into the semantic meaning of physiological data, its application potential within HCI, and reliable data recording possibilities.

### 4.1 Participants

We invited one data visualization expert with three years of experience, one VR designer (four years), and two experts researching physiological data for interaction design (over six and four years, respectively). One of the latter experts focused on their application in VR and the other across application contexts. Two of the experts self-identified as female, and two as male. We recruited them via the research institution's network. All gave informed consent.

### 4.2 Approach and Setup

Similarly to Lee et al. [74], we pre-selected skin conductance, breathing rate, and heartbeat, which belong to the most commonly researched data in this context. The experts first brainstormed about the physiological data to be applied using Post-its and pen and paper. They considered current technical possibilities to measure the data and their effects on the user experience regarding helping players to feel socially connected to others and to solve the riddles faster. Afterward, we asked the experts to sketch information visualizations with provided pens, blank paper, and printed images from the VR scene. They could also explore and adapt their ideas in the VR scene (see Figure 3). The latter enabled situated sketching, which supports visualizing information in 3D contexts by considering its positioning, size, and effect in dependence on the surroundings [14]. The workshop took about two hours and was audio recorded. We evaluated the workshop data by analyzing the sketches and Post-its in combination with the audio recordings. For this, we reviewed visualization and biodata suggestions and mapped verbal argumentations for and against each based on the transcribed statements.



(a) (b) (c) (d)

Fig. 3. Expert Design Workshop: a) Brainstorming about physiological data, b) pen and paper sketching, c) 2D sketching on pictures from the environment, and d) situated sketching in the 3D VR escape room.

### 4.3 Results

The experts mainly discussed breathing rate (BR) and heartbeat in the form of Electrocardiogram (ECG) data for the gaming scenario, as both are established in games and movies to increase tension and emotional reactions. They ignored skin conductance because it is less known and, thus, harder to understand. In contrast, the experts emphasized that BR and ECG could be measured and applied to indicate excitement about solving a riddle or to *"highlight others' SOS points"* (Expert 2). In the end, the experts recommended focusing on heartbeat data as current measurement possibilities are more reliable, particularly during movements, and its visualizations are well-known to trigger associations about a person's emotional state [8]. Yet, it would require additional information to interpret the data correctly and differentiate i.e. between stress and excitement. To this end, the experts suggested contextualizing the data by combining it with the player's movement data and, thus, spatially and temporally integrating it into the VR scene. The experts expected such visualizations to trigger players' competitiveness or support collaboration by indicating how fast others solved a riddle or where to find the next clue. They briefly also discussed potential privacy issues. In line with Lee et al. [74], our experts agreed to provide the data in an anonymized format, which does not allow linking the performance to a specific player profile or keeping the profile anonymous. The experts preferred only to visualize the best player's anonymized data to foster the players' competitiveness or several players' data to emphasize common points of interest. They also discussed who users wanted to be socially connected with, and for what purpose. As many games are played with friends, they proposed to reflect a more personal one-to-one relationship compared to the broader and less intimate social relationships with other players from the same game community (NUMBER OF PLAYERS). This could be visualized through ECG lines or symbolic heart icons that dissolve shortly. Both visualizations are commonly well-known visualizations for heartbeat data [68] as ECG lines are commonly used in medical contexts and heart icons in social media and research (VISUALIZATION STYLE). Other visualization suggestions were avatar ghosts from the asynchronous players or cloud-like shapes that dynamically move through the room.

### 4.4 Design Decision on the Heartbeat Visualizations

Considering the results presented above and the findings from prior work, we decided to explore the effect of visual feedback similarly to Lee et al. [74]. This means we focused on heartbeat visualizations considering two times two visualization dimensions: the NUMBER OF PLAYERS, for which heartbeats were shown (single versus multiple) with the VISUALIZATION STYLE (ECG lines versus heart icons). We base our decision on multiple reasons: The heart icon is a broadly used symbol to communicate emotions [41]. Similarly, ECG lines are well-known visualizations from the medical context that comply with the raw data visualization style of other previous work [2, 39, 71]. Since we aimed at triggering social connectedness with the visualizations, we wanted

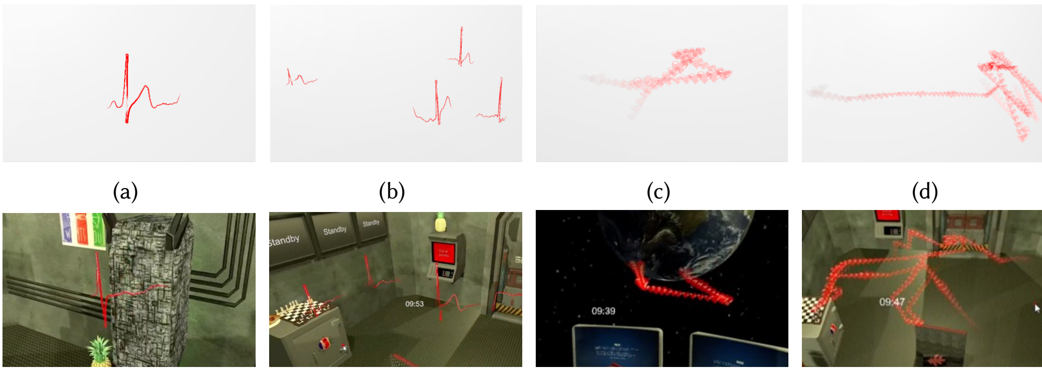



Fig. 4. Four heartbeat visualizations without and in context: a, e) single ECG line, b, f) multiple ECG lines, c, g) single heart icons, and d, h) multiple heart icons.

to use well-known heartbeat visualization styles that participants could immediately recognize. Further, our experts advised us to explore the NUMBER OF PLAYERS. This decision is additionally strengthened by prior works' focus on exploring shared heartbeat data either to enhance one-to-one relationships [74, 77, 81] or share it with multiple people during, e.g., gaming [36, 41]. This resulted in testing symbolic heartbeat visualizations in the form of heart icons versus more scientific ECG lines combined with single versus multi-player data. Lastly, we decided to connect the heartbeat data to players' movements through the escape room to spatially and timely contextualize the data as suggested by the experts. Figure 4 shows all four visualization conditions. We decided against adding sound or other heartbeat-related feedback, e.g., sound or haptic feedback, to reduce potential bias. While we combined various arguments for making our design decision, we also saw the risks that the contextualized multi-player visualizations might distract participants more than support them. Thus, we introduce a second hypothesis:

**H2** Providing multiple individual ECG data visualizations distracts players and reduces their performance more than only one person's ECG data visualization or no visualization.

## 5 VR ESCAPE ROOM STUDY

The workshop resulted in four visualizations of heartbeat data (see Figure 4). Following these results, we conducted a within-subjects lab study applying a mixed-method approach with N=34 participants. In the study, we compared the four visualizations and one baseline condition with no visualization. Accordingly, we developed five escape room stories, one for each condition. We created the visualizations by gathering data in a pre-study (N=4). The study received approval from the authors' research institution's ethics board.

### 5.1 Equipment and Physical Setup

All participants experienced the scenes through a Vive Pro [26] within an empty 3x3m$^2$ space. We acquired ECG data with a Polar H10 chest band (Polar, Finland) placed over the xiphoid process of the sternum below the chest muscles. Raw data were sampled at 130 Hz and streamed within the Lab Streaming Layer framework[12], which is a broadly applied technique for different technologies[12, 33], to the acquisition PC (Intel®Core™i7-9700 CPU @ 3.00GHz, 32GB RAM).

[12]https://github.com/labstreaminglayer/, last accessed Feb. 13th, 2023

### 5.2 Game Setup and Concept

We prepared the virtual escape room by implementing three different riddles for each story, including three hints for each riddle. We provided the hints after a player did not proceed for 2:30 min. Players needed to complete each riddle subsequently to unlock the exit. We integrated a timer to increase the pressure, giving players ten minutes to exit.

### 5.3 Procedure and Tasks

First, all participants gave informed consent about the data gathering and processing. Before recording, we moistened the ECG electrodes with lukewarm water and asked participants to put on the chest band. Because this work investigates the differences evoked by the various visualizations rather than the physiological reactivity of the ECG signal, we chose not to include a baseline recording in our approach. Afterward, they entered a training scene in VR. We asked them to complete simple interaction tasks relevant to the escape room game, such as grabbing, releasing, and throwing an object, and then entering the first story. We randomized the order of the stories and visualizations with a Graeco-Latin square in R2022.07.1. On entering a scene, participants were introduced to the storyline and the task. They were put into the role of the space station's captain, who needed to exit the room within the next 10 min because of, for example, an approaching alien invasion or leaking oxygen. In between stories, participants took a short break and filled out questionnaires to rate their immediate experiences. We asked them to compare their experiences in a final questionnaire and completed the session with a short interview about their reasons for indicated playing preferences and observed behaviors. After completion, participants received their reimbursement, 5€ / 30 min. The study took between 60 to 90 minutes, depending on the participant's performance in the game.

### 5.4 Pre-Study: Data Gathering and Visualization Creation

The pre-study aimed at gathering real-player ECG data to create the visualizations. To this end, we tested our VR scenes with four participants (two self-identified as male and two as female) while acquiring their ECG and head-tracking data. We asked them about their gaming experience to assess potential issues with the scenes through open-ended interview questions. Additionally, we took time measurements and counted the number of hints needed to complete each story. The results showed that it took them 6.14 min on average to complete each scene (*SD*=2.27 min.) using only eight of 60 hints. Two times participants needed longer than ten minutes to exit. The participants did not report any issues with the scenes besides finding it harder at the beginning than at the end. As this impression occurred consistently, we attribute a certain learning effect that occurs over time. They reported having fun playing the game and feeling good about their performances. We consider these results to confirm having created balanced escape room stories regarding difficulty and duration. For the visualizations, we extracted the Heart Rate (HR) from the ECG and processed the raw signal via the Neurokit Python Toolbox [78] from all VR scenarios and each participant. The ECG signal was first filtered with a Finite Impulse Response (FIR) band-pass filter (3–45 Hz, 3rd order) and then segmented with Hamilton's method [50]. From the computed HR per participant, we displayed HR visualizations ranging from 85.71 bpm to 112.08 bpm, with an interquartile range of 26.36 bpm, in each VR scenario. We combined each heart rate data with the spatial movement (head tracking data) over time so that we ended up with four individual heart rate visualizations, one for each participant per room, that pulsated according to the single player's heartbeat. For the single visualizations, we considered only the fastest (aka best) player's data per story, whereas, for the multi visualizations, all data was visualized in four separate heartbeat visualizations. The visualizations started immediately at the beginning of a story and disappeared after the completion time from when the previous participants had exited.

### 5.5 Independent Variables

We defined the heartbeat visualizations as our independent variable with five levels: i) a single ECG line of one player, ii) multiple ECG lines of four prior players, iii) a line of beating heart icons of one player, iv) multiple lines of heart icons of four players, v) no visualization.

### 5.6 Dependent Variables

To respond to **H1**, we tracked participants' gaming experience with the Player Experience Inventory (PXI) questionnaire [1, 45], their feeling of social connectedness with the Inclusion of Other in the Self Scale (IOS) [4, 31] using the material by [49] and the Social Presence of the Game Experience Questionnaire (GEQ) [58, 86], which allow for content sensitivity and validity [29] as dependent variables. For **H2**, we gathered the game completion times, the number of hints needed, and participants' gaze. We additionally gathered head position data, and presence according to Slater et al. [99] to assess participants' level of immersion in the game.

We also added open-ended questions in the final questionnaire about participants' perception of the individual visualizations regarding their size, pulsation, and positioning in the scenes and asked participants to rank them according to their perceived usefulness, triggered social and emotional connectedness, level of annoyance, and distraction. Participants were also prompted to explain the reasons for their rankings. To gain further insights, we asked participants to rate statements regarding their experiences with the evaluations on a 7-point Likert scale after each condition that contained a visualization (i.e., excluding the baseline condition with no visualization). Lastly, we completed each participation with a short semi-structured interview of three to five minutes about the effect and perception of the visualizations. The questions asked to the participants were: What did you think about the visualizations? Did the visualizations help you in any way? Depending on the participants' answers, we followed up with unstructured questions concerning, e.g., the visualization details that supported or distracted them most or which visualization they preferred for what reasons. As the design of the visualizations might influence the gaming experience (**H1**) and distract them (**H2**), we collected these qualitative data to explain the results of both hypotheses. We screen-recorded participants' activities with OBS (Open Broadcaster Software, Version 72.2.4) and audio-recorded the interviews. We provided the questionnaire data in a survey tool from the authors' research institution, and kept the audio, video, and tracked VR data recordings on internal university-shared storage.

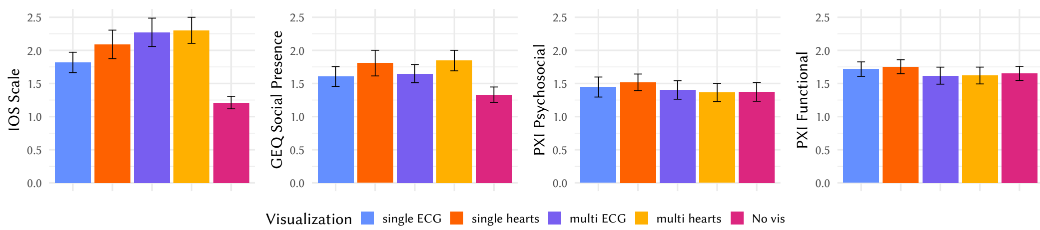
### 5.7 Participants

We recruited participants (N=34) via the university's mailing lists. 18 participants identified themselves as female, 16 as male. The average age was 25 years old (*SD*=4.4 years). Six had no experience in VR, five had tried it once, 13 two to five, and five more than five times before. Conversely, five had never played an escape room game before, ten once, 11 two to five, and eight more than five times.

## 6 RESULTS

We provide inferential statistics to investigate our hypotheses, which we describe below. For most data, we conducted Shapiro-Wilk normality tests and applied either an RM ANOVA or the Friedman tests if the normality assumption was violated. For significant ANOVAs, we report the generalized eta-squared $\eta_G^2$ as an estimate of the effect size. As suggested by Bakeman [6], we classify these effect sizes using Cohen's interpretation [24] as small (> .0099), medium (> .0588), or large (> .1379). For Friedman tests, we report Kendall's W classifying it according to Landis and Koch [73].

### 6.1 Social Connectedness, Presence, and Player Experience




(a) IOS Scale (b) GEQ Social Presence (c) PXI Psychosocial (d) PXI Functional

Fig. 5. The results for: (a) the Inclusion of Self in Other Scale (IOS), (b) social presence (GEQ), and of the Player Experience Inventory (PXI): (c) *psychosocial* and (d) *functional*. All error bars depict the standard error.

Regarding the social connectedness (**H1a**), we evaluated the **IOS** with a Friedman's rank sum test revealing a significant ($\chi^2(4) = 37.85$, $p < .001$) influence of the Visualization on the participants' answers with a small ($W = .29$) effect size. This approach aligns with Dey et al. [31]'s work. Conover's post-hoc test revealed significantly lower ratings for no visualization compared to multi ECGs, multi heart icons (both $p < .001$), and single heart icons ($p < .01$). The difference to the single ECG was not significant ($p > .05$) (see Figure 5a).

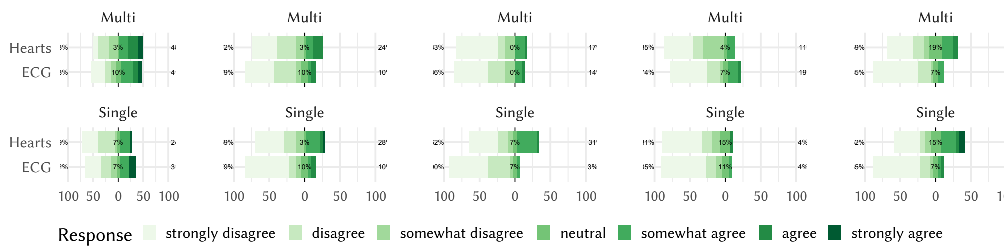
Results concerning the **social presence** as measured according to the GEQ [58, 86] indicated a significant ($\chi^2(4) = 22.18$, $p < .001$) influence of the visualization on the social presence with a small ($W = .21$) effect size. Conover's post-hoc test confirmed significantly lower scores for no visualization ($\mu = 1.3$, $\sigma = 0.6$) compared to single heart icons ($\mu = 1.8$, $\sigma = 1.0$, $p < .01$), multi heart icons ($\mu = 1.9$, $\sigma = 0.8$, $p < .001$) and multi ECGs ($\mu = 1.7$, $\sigma = 0.7$, $p < .01$). We could not find a significant difference in single ECG ($\mu = 1.6$, $\sigma = 0.8$, $p > .05$). Figure 5b shows the results.

Participants' feeling of **presence** did not reveal any significant differences between the conditions ($F_{4,132} = 1$, $p > .05$), which we analyzed with an RM ANOVA.

We assessed the **PXI** (**H1b**) calculating the average values of the *psychosocial* and *function* questions on a scale from -3 to 3 as proposed by Abeele et al. [1]. For the group of psychosocial questions, we found mean values ranging from $\mu = 1.4$, $\sigma = 0.8$ (multi heart icons) to $\mu = 1.5$, $\sigma = 0.7$ (single heart icons), see Figure 5c. For the group of functional questions, we found mean values ranging from $\mu = 1.6$, $\sigma = 0.7$ (multi heart icons) to $\mu = 1.8$, $\sigma = 0.6$ (single heart icons), see Figure 5d. The analysis using Friedman's rank sum test revealed neither a significant influence of the visualizations on the psychosocial ($\chi^2(4) = 5.55$, $p > .05$) nor any impact on the functional ($\chi^2(4) = 3.92$, $p > .05$) scores.

### 6.2 Results of the Custom Likert Scale Questions

For the analysis of the custom Likert questions, we analyzed the participants' answers considering the VISUALIZATION STYLE (ECG vs. Hearts) and the NUMBER OF PLAYERS (Single vs. Multi) as factors to isolate their respective influence and unveil interaction effects between the factors. We performed an Aligned-Rank Transformation (ART) as proposed by Wobbrock et al. [107]. For post-hoc analysis, we applied the ART-C procedure as proposed by Elkin et al. [38]. The Likert scale results reveal the level of understanding of other players' activities (**H1c**).




(a) Distraction (b) Support (c) Emotional Attachment (d) Understanding (Feelings) (e) Understanding (Actions)

Fig. 6. The ratings to our 7-point Likert scale questions: the perceived (a) distraction, (b) emotional attachment, (c) support in playing the game, and understanding of (d) feelings, and (e) actions of other players. For full questions, please refer to the text.

*The visualization distracted me from playing the game.* The analysis revealed a significant ($F_{1,28} = 14.13$, $p < .001$) main effect of the NUMBER OF PLAYERS on the participants' ratings with a large ($\eta^2_G = 0.34$) effect size. Post-hoc tests confirmed significantly lower distraction ratings for the single conditions than multi conditions ($p < .01$). We did not find a significant main effect for the VISUALIZATION STYLE ($F_{1,28} = 0.29$, $p > .05$) or an interaction effect between the conditions ($F_{1,28} = 3.73$, $p > .05$) (see Figure 6a).

*The visualization supported me in playing the game.* The analysis indicated a significant ($F_{1,28} = 5.34$, $p < .05$) main effect of the VISUALIZATION STYLE on the perceived support in playing the game with a large ($\eta^2_G = 0.16$) effect size. Post-hoc tests confirmed significantly higher perceived support for heart icons than ECG visualizations ($p < .05$). We did not find a significant main effect for the NUMBER OF PLAYERS ($F_{1,28} = 0.54$, $p > .05$) nor an interaction effect between the two factors ($F_{1,28} = 0.06$, $p > .05$) (see Figure 6b).

*The visualization made me feel emotionally attached to other players.* We found a significant ($F_{1,28} = 4.39$, $p < .05$) main effect of the VISUALIZATION STYLE on the reported emotional attachment of our participants with a large ($\eta^2_G = 0.14$) effect size. Post-hoc tests showed significantly higher ratings for the heart icons than the ECG visualizations. We did not find a significant ($F_{1,28} = 1.02$, $p > .05$) main effect for the NUMBER OF PLAYERS. However, we found a significant ($F_{1,28} = 13.17$, $p < .01$) interaction effect between the two factors with a large ($\eta^2_G = 0.32$) effect size. While we found comparable ratings for single- and multi-player for the heart icons conditions ($p > .05$), we found significantly ($< .05$) higher ratings for multi-player compared to single-player for the ECG conditions (see Figure 6c).

*I feel I understood how others had felt in the VR through the heartbeat visualization.* The analysis did not reveal any significant main (VISUALIZATION STYLE: $F_{1,26} = 0.54$, $p > .05$, NUMBER OF PLAYERS: $F_{1,26} = 2.25$, $p > .05$) or interaction effects ($F_{1,26} = 0.34$, $p > .05$) for the participants' understanding of other players' feelings (see Figure 6d).

*I feel I understood what others had done in the VR through the heartbeat visualization.* We found a significant ($F_{1,26} = 16.62$, $p < .001$) influence of the VISUALIZATION STYLE on the reported understanding of participants with a large ($\eta^2_G = 0.39$) effect size. Post-hoc tests confirmed significantly

($F_{1,26} = 16.62$, $p < .001$) higher reported understanding for the heart icons compared to ECG visualizations ($p < .001$) (see Figure 6e).

### 6.3 Participant Performance

We analyzed the required time to finish all riddles and the number of hints used in a room to measure the participants' performance (**H2**). The first six participants had to be excluded for missing data due to technical issues, resulting in N=28 data samples for the hint measurements. We found mean **times** ranging from $\mu = 6.5$ min, $\sigma = 2.2$ min (no visualization) to $\mu = 7.1$ min, $\sigma = 2.3$ min (multi heart icons). An RM ANOVA did not reveal a significant ($F_{4,108} = 0.22$, $p > .05$) influence of the visualization on the required time.

In contrast, we found the lowest number of used **hints** for the no visualization condition ($\mu = 1.6$, $\sigma = 1.3$) and the highest number of used hints for the multi heart icons conditions ($\mu = 2.1$, $\sigma = 1.7$). Due to the hints being count data, we fitted Poisson regression models to explain the number of hints used from the visualization and applied Type III Wald Chi-Square tests for significance testing. However, the analysis did not indicate a significant ($\chi^2(4) = 2.93$, $p > .05$) influence of the condition on the number of hints used.

### 6.4 Qualitative and Ranking Results of the Visualizations

Lastly, we share the qualitative and ranking data results. We transcribed all audio recordings for the interviews and conducted a reflexive thematic analysis following an inductive approach [13] on the transcripts and the written explanations about the ranking choices. For this, one author first familiarized with the data to generate the first codes, based on which they constructed broader themes. Then, they iterated on these themes deciding on the themes that were finally consolidated into three themes including 27 unique codes in total: Social Connectedness (ten codes), Game Play (ten), and Visualization Design (seven). Additionally, we supplement the thematic results with the ranking results. For this, we provide the total counts of how and how many participants ranked the different visualizations.

*6.4.1 Social Connectedness.* This theme comprises participants' opinions on their perceived social connectedness triggered through visualizations. The brackets contain the number of participants agreeing.

*Visualizations triggered diverging understanding.* In the interviews, fourteen participants explicitly confirmed having felt socially connected to the previous players through the visualizations. Another five participants reported that the visualizations helped them to understand other players' actions in the gameplay and two emphasized the derived understanding about other's emotions, which they associated with the pulsation; e.g., *"If they had discovered something and were super excited, I feel like yea.. that's a pulse."*, P16. The feeling of social connectedness particularly occurred when multiple visualizations gathered at one location or when participants perceived time parallels such as when reading the introduction to each story at the same time as others had done. In contrast, two categorized the visualizations as additional information without feeling any connection and three did not understand the visualizations' meaning and found them rather ambiguous. Nine participants did not explicitly state any social connectedness in the interviews.

*Heart icons triggered the greatest social connectedness and emotional attachment.* The multiple heart icons triggered the greatest social connectedness (18), followed by the multiple ECG (8), single heart icons (4), the single ECG (2) and without visualization (2). Thirty participants ranked the condition without visualization lowest in this category, three the multiple ECG and one the single ECG. Participants felt particularly more connected through the heart icons because they are familiar symbols (*"I relate [the hearts to] the life level, so I can see if the others are still alive or took damage [...]."*, P29, easier to understand *"Heart is a symbol of connection where ECG symbol was too scientific and I didn't understand how to process it consciously"*, P30 and because they triggered participants to relate others' activities to their own (*"the more you see where they went the more I felt connected to them, especially if they helped me find clues"*, P9). In comparison, single visualizations seemed to facilitate a more direct, personal connection for the six participants who ranked them highest, e.g., *"I thought about standing next to somebody else"*, P6, or *["The] connection feels stronger than to [a] group"*, P2. Participants also felt the greatest emotional attachment to the multiple heart icons (11), followed by the multiple ECG (10), single ECG (5), single heart icons (4), and no visualization (4).

*6.4.2 Game Play.* This theme consolidates participants' strategies for dealing with the visualizations in the game. The results emphasize that no visualization supported the perceived game performance best.

*No visualization was ranked most useful.* Regarding usefulness, 19 ranked the baseline condition highest, followed by either multiple (7) or single heart icons (6). The single and multiple ECGs were selected by one participant each as the most useful. Participants explained their choice with *"no visualizations, means no distraction"*, P8. The heart icons were easier to follow because their shapes were clearer to see, yet subtle. Additionally, they liked the multiple visualizations (ECG and hearts) for navigating in the environment (*"Multiple is better as I get to see more players."*, P30). The least useful was the multiple ECG (13) because they were perceived as distracting and hard to understand. Four participants further stated in the interview that they ignored the visualizations and focused solely on solving the riddles fast, e.g., P28 *"I think it was good that there were no other people, just me."*.

*Multiple ECG were most distracting and annoying.* 17 participants ranked the multiple ECG as the most distracting and annoying visualization, followed by the multiple heart icon (14 each). The main problem with the multiple player's heartbeat visualizations was clutter and distraction from the actual tasks (*"Too many visualizations were distracting and blocked the vision."*, P26). Having no visualizations was ranked the most distracting by two and most annoying by one participant. Similarly, two participants ranked the single ECG as the most annoying and one as the most distracting. None ranked the single heart icons the highest in either category. At the same time, ten participants mentioned having used multiple visualizations to see where *"people may be clustered somewhere, so that might be a clue."*, P6. Participants also reported having sometimes missed the single visualizations because of having concentrated on solving the riddles, having looked at another area of the escape room, or because the visualizations quickly disappeared (e.g., *"I saw an ECG line in the beginning and that was it"*, P1). Three participants understood the visualizations' only over time indicating that the game partly interfered with the time needed to interpret them.

*6.4.3 Visualization Design.* This theme includes the visualizations' style and design and how that impacted the gaming experience and social connectedness.

*The Visualizations' Effect on the Game Character.* Overall, the participants who made use of the visualizations perceived them as either collaborative or competitive stimuli in the form of feeling motivated to explore certain areas or comparing their own performance during the gameplay; *"The more it was right in front of me the more pressure I felt to solve the puzzle"*, P30. Comparing the results across visualizations, in total 18 participants appreciated the guidance deriving from seeing other players' movements to identify *"important spots"*, P27. Six found the visualizations' positioning too prominent ending up obstructing their sight and interrupting their concentration. This was mentioned particularly in relation to the visualizations' size *"The size was sometimes disturbing* *but helpful. If there are no visualizations there is no 'help' for the player"*, P20. In comparison, nine participants blended them out and one participant found the visualizations helpful when pointing toward one location but distracting when they moved in different directions.

*The Making and Interpretations of the Heartbeat Pulsation.* The heartbeats' pulse simulations triggered diverse opinions. Ten found it helpful to find the next clue and related stronger beats to others' increased excitement about solving a riddle; e.g., *"Higher frequency = more excitement = probably found a clue"*, P18. The pulsations also made it appear *"more real"* (P3) and facilitated participants to relate to other players' states. Three felt disturbed by the pulsation and the majority (19) found it a natural characteristic of the heartbeat (e.g., "if it stopped I would be distracted and concerned", P7) without mentioning a deeper feeling of connectedness. One participant indicated that they only felt stressed the first time they saw it. In comparison to the visualizations' movement and the number of players, the pulsation seemed less important for the gaming experience (*"It was not so much the amplitude of the heartbeat, but more where they are and how many were at the same place so that definitely motivated me"*, P33) and more critical for the social connectedness.

## 7 DISCUSSION

In our work, we hypothesized that **H1:** displaying asynchronous players' ECG data that is temporally and spatially integrated improves players' (**H1a)** social connectedness, (**H1b**) gaming experience and (**H1c**) understanding of other players' activities compared to having no data visualization. Our results support the hypothesis for three of four visualizations regarding social connectedness and both heart icon visualizations on understanding. However, the gaming experience differs between visualizations and stays inconclusive because of mixed feedback to their design and embeddedness. Additionally, we assessed the effect of the NUMBER OF PLAYERS, hypothesizing that **H2:** providing multiple individual ECG data visualizations distracts players and reduces their performance more than only one person's ECG data visualization or no visualization. Our results support the hypothesis that multiple visualizations trigger greater confusion but stay inconclusive about the influence on the player's performance. In the following, we discuss the visualizations and derive three design recommendations (**DR1-3**), and the potential of embedding physiological data visualization in asynchronous VR gaming scenarios.

### 7.1 The Visualizations' Effect and Deducted Design Recommendations

Aligning our results with prior work, visualizing users' heartbeats in VR increases immersion and emotional awareness [74, 83, 89] but remains challenging to visualize [43]. In our work, we observed different effects particularly related to the VISUALIZATION STYLE: First, the symbolic heart icons had a significant positive effect on social connectedness in the single and multi-player conditions, were easier to understand, and scored higher in supporting users in playing the game (see Figure 6b) than ECG visualizations. We explain these results with the familiarity of a symbolic heart icon, which is a well-known metaphor for socio-emotional information [60, 74]. Findings by, e.g., Pinilla et al. [88] suggest that rounded visualization, such as the heart icons, are perceived as more aesthetically pleasing and, thus, trigger more positive associations. Referring these findings to a more broad scale, we suggest to: **DR1.** Apply well-known symbols of social and emotional meaning to visualize physiological data to increase social connectedness.

Second, all but the single ECG visualization had a significant positive effect on **social connectedness** and social presence but stayed inconclusive on the **gaming experience**. While the multiple visualizations were perceived as the most distracting, half of the participants used the visualization to find new clues, notably when multiple lines overlapped and marked common points of interest. This clash of distractions, while also providing guidance, questions the visualizations' scalability.

A possible solution could be found in unobtrusive design techniques. For example, Bakker [7] and Renner and Pfeiffer [91] introduced means that enable users to focus on primary tasks (here: escaping the room) while providing secondary task information (here: other player's state) through peripheral interaction. Yet, the question remains of how to generate this "crowd knowledge" effect without disrupting the main game goal. Since we are not able to answer this question for now, we recommend to: **DR2.** Balance the amount of asynchronous player's data visualizations for scalability and understanding when used as secondary task information.

Third, the visualizations pulsated according to the recorded heartbeats. These dynamics made the visualizations appear more real, triggering some participants to relate theirs to other players' situations. In line with prior work, we attribute the dynamic visualization elements to support the communication of others' emotional state [31, 74] and their contextualization to increase understanding of spatially linked interactions [16]. Accordingly, we recommend to: **DR3.** Include dynamic visualization elements to support users' impression of connecting to other real, asynchronous players.

### 7.2 The Potential of Shared Physiological Data in VR Games

Shared physiological data can increase the understanding of other's social and emotional states [28, 31]. Designing for increased social connectedness and presence can further impact users' enjoyment [15, 67] and gaming experience [66]. Based on that, we discuss the effect and the potential of shared physiological data in asynchronous VR gaming scenarios.

*7.2.1* ***Displaying asynchronous players' physiological data can trigger competitiveness or foster collaboration in single VR games***. Participants connected the visualizations to asynchronous players' progress and compared it to their own. The visualizations either increased the collaborative or competitive game character. The visualizations' movement and pulsation allowed insights about in what order others had solved the riddles and their level of excitement. This information provided insights into other players' efficiency and strategies, which some participants used to adapt their playing strategy. In that sense, the visualizations enabled collaboration between the asynchronous players and our participants. Relating this to the competitive character of the game, the result is similar to D'Souza et al. [36]'s findings about shared physiological data in a synchronous, competitive gaming scenario in which players used the transmitted data to outperform each other. Consequently, shared asynchronous physiological data can foster a sense of competitiveness or collaboration that trigger players to adapt their game strategy.

*7.2.2* ***Asynchronously shared physiological data extends current in-game social cues***. Game designers have applied in-game movement traces as collaborative social cues[5,6,7]. For example, in Death Stranding, single-mode players can spot other players' footsteps or see desire paths created by multiple users passing through an otherwise untouched area [69]. Compared to our work, these in-game cues are mainly positioned on the ground. However, the third coordinate (height) was important information for understanding where the asynchronous players had potentially found the next clue, i.e., under the chair. Thus, our work added a level of information to the movement data by exploring the socio-emotional information of physiological data visualizations, similar to Mevlevioğlu et al. [82]'s or Dey et al. [32]'s works. As such, asynchronously shared physiological data has the potential to extend the currently applied movement cues in VR games and additionally foster empathy, understanding, and social connectedness.

*7.2.3* ***In-game shared physiological data provide implicit, yet still ambiguous communication cues***. Social VR contexts, including games, can be misused for harmful social behavior and communication [9, 11, 63]. In our work, the heartbeat visualizations served as implicit social cues only without the possibility for asynchronous players to leave messages actively. We played the visualizations synchronously with the current players' performance. This created an effect of co-location, which contributes to the feeling of playing together and turns a single-player game into a social experience [102]. Yet, some participants also struggled to understand the visualizations' meaning, particularly when they felt distracted by them. This might be because by aiming for implicit communication cues, there is also no clearly communicated message such as a text saying "*look here*". In contrast, the user is responsible for deciphering the visualizations' meaning. By embedding the visualizations temporally and spatially, we reduced the ambiguous definition of physiological data [28, 81]. However, it seems like the visualizations need to be better integrated into the game's story to provide a clearer purpose besides their implicit social meaning.

## 8 FUTURE WORK AND LIMITATIONS

We present future work that could address current limitations and explore further research opportunities.

### 8.1 Methodological Limitations

Our methodological approach comprised limitations through our design choices for the visualizations and game scenarios. For example, we tested the visualizations only in combination with players' movement data. This enabled our results to reflect the limitations and advantages of embedded physiological data and to assess their applicability for future game designs. Yet, this means that all measured effects cannot only be explained with heartbeat visualizations. Consequently, it would be interesting to compare the results with the effect of asynchronously shared but non-contextualized heartbeat data. The gaming experience is also biased through the storylines and types of riddles. Furthermore, solving five escape room scenarios in a row might have caused fatigue in participants. However, we limited the time for each scenario and observed participants slightly improving in solving the riddles. We conducted the pre-study to gather the heartbeat data and to test for differences in the level of scenario difficulties. As none of the participants noted any differences and the performances stayed comparable, we considered the bias balanced for the study context.

### 8.2 Extending to Other Physiological Data

We only employed ECG signals as an input for the visualizations and allowed passive interaction. However, asynchronous social VR paradigms employed other physiological measures such as electroencephalographic (EEG) frequencies to increase affective interdependence [96] or empathy by physiological synchrony [97], or eye-tracking to create situational awareness [110]. Future work could therefore explore different physiological data visualizations, for example, to index the attentional state of participants [21, 25], which could further help them to focus on specific target areas within the VR. To exploit the advantages of the multiple visualization conditions, game designers could add control features for users to decide when to see other's traces or enable bi-directional data sharing for true asynchronous communication.

### 8.3 Mitigating loneliness through asynchronously shared physiological data

Our approach of displaying asynchronous players' heartbeats resulted in significantly higher feelings of social presence and relations in three of four visualizations. It shows the potential of sharing physiological data as social cues without having a co-player present to mitigate loneliness that may be experienced in solo games or other contexts [18, 66, 75]. Yet, our work did not test for the visualizations' effect on perceived loneliness. Previous work [53, 64] highlighted the danger of having "poor-quality" [53] social connections that can even worsen the feeling of loneliness.

Thus, future work should research data-sharing concepts that prevent and do not worsen potential loneliness.

### 8.4 Application Contexts

We explored our concepts in an escape room game, which elicited certain expectations from the participants. For example, their first intention was to exit the scene and not socially connect with others. This might differ for other games and shows that increasing social connectedness is not useful for all cases. We see potential in exploring the concepts further for other contexts [28]. Future work could, for example, introduce asynchronously shared physiological data in other social VR contexts, such as the bar scenario as presented in Lee et al. [74], in which physiological data was shared synchronously additionally to a user's avatar. Extending this about asynchronous users' data could impact the space's atmosphere and perceived liveliness. Similarly, in the physical world, urban interaction designers aim to design environments that connect people [57] and "more-than-human beings" [105]. Sharing the physiological data of animals in situ could raise awareness of the shared habitat and trigger potential behavior change.

### 8.5 Privacy versus Contextualization

Lastly, previous work identified privacy issues regarding sharing one's physiological data with others [56, 74]. In our study, we kept the data separate from other personal information, which, however, made it also harder to understand. This might not be possible in a regular game community that uses a high-score system and publicly announces the best players. Such scenarios require a thorough exploration of data privacy and user rights. Altogether, there is considerable research potential for exploring shared physiological data to design asynchronous social VRs and other contexts [20], for which our study provides first insights.

## 9 CONCLUSION

This work is one of the first to explore embedded and asynchronously shared physiological data visualizations to induce social connectedness in VR games. Focusing on heartbeat, our results showed the data's significant positive effect on social connectedness in three of four visualizations. Our work contributes three design recommendations for designing asynchronously shared physiological data that we consider relevant for VR games and other social VR contexts. It also highlights the potential of embedded physiological data to increase a game's collaborative or competitive character and, thus, implicitly foster social connectedness between asynchronous players. While our study explored the effect in an escape room case study example, our results and discussion highlight the potential for extension to other social and single-user contexts to increase social connectedness within VR or other realities in future work.

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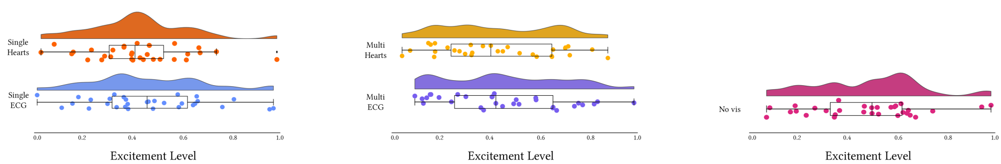


(a) (b) (c)

Fig. 7. “Excite-O-Meter” results: Raincloud plot of the differences among conditions concerning the excitement level. The ‘cloud’ illustrates data distribution, while the ‘rain’ depicts the jittered data points. In the boxplots below, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively for the Excitement Level. In (a) we depict the distribution of single visualizations, in (b) we show multiple visualization, and finally, in (c) we plot the no visualization condition.

# A APPENDIX

## A.1 Electrocardiogram

We processed the ECG signal via the Neurokit Python Toolbox [78], as we did for the pre-study, see subsection 5.4. With this, we aimed to assess whether any of the visualization impacted participants' level of excitement.Together with Heart Rate (HR), we also used Heart Rate Variability (HRV), as derived from the standard deviation of the normal-to-normal intervals (SDNN). We removed one participant (P22) in the ECG analysis due to missing data. Neither the Heart Rate (HR), Heart Rate Variability (HRV), nor Excitement Index provided any significant differences.

*A.1.1 Heart Rate (HR) and Heart Rate Variability (HRV).* We conducted a Friedman's rank sum test for the HR and HRV. The results did not reveal a significant difference across visualizations on the HR ($\chi^2(4) = 3.36$, $p > .05$). We also ran a Friedman's test on SDNN values, which found no significant effects of visualizations on the HRV ($\chi^2(4) = 5.62$, $p > .05$).

*A.1.2 Excitement Index.* We fitted a linear mixed-effects model (estimated using REML and nloptwrap optimizer via the R package lmerTest [72]) to predict participants' “Excite-O-Meter” level as a function of the visualizations, as analyzed in [89]. To account for the repeated-measures structure in our study, we added a random intercept for every participant to our model. We then applied an ANOVA to the outcomes of the model. Results showed no significant differences across the levels of visualizations ($F_{1,126} = 0.48, p = .44$). Results are depicted in Figure 7.

## A.2 Thematic Analysis

Table 1. The thematic scheme including 3 themes and 27 unique codes from the interview coding.

| Themes | Codes |
|---|---|
| Social Connectedness | preference to be alone, feeling of being socially connected, little companion, self-reflection, relating to other's emotions, understanding others' actions, neutral, timing, indirect/implicit, sense of belonging |
| Game Play | navigation, practical, ignoring visualizations, collection of points, learning, following the wrong track, independence, adaptation, wrong game type |
| Visualization Design | size, movement, distraction, clutter, ambiguity, heartbeat, realistic |

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