Exploring the Design Space for Multi-Sensory Heart Rate Feedback in Immersive Virtual Reality

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ABSTRACT

Virtual Reality (VR) interfaces have been shown to be able to trigger different emotions in users. However, earlier VR interfaces did not provide users with their own heart rate feedback and the effect of such a feedback on overall experience has not been investigated. In this research, we investigated whether providing heart rate feedback enhanced the participant's experience of using VR and we explored the design space of different types of multi-sensory heart rate representations. Through a within-subjects study, and using subjective measurements, we found that participants enjoyed seeing their heart rate feedback when experiencing VR environments. From the different types of heart-rate representations, audio-haptic feedback was the most preferred while visual feedback was reported as being distracting. We report on the implications of this for designing VR experiences and directions for future research[1].

CCS CONCEPTS

• Human-centered computing~Virtual reality • Human-centered computing~User studies

KEYWORDS

Virtual Reality, Physiological Data, Heart Rate, Emotion, User Study

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1 INTRODUCTION

Virtual Reality (VR) is an interactive medium that can provide multi-sensory (audio, visual, and haptic) feedback and immersive experiences to create a deep sense of Presence. The use of VR is now a commonplace in multiple application domains such as gaming, movies, education, and therapy. The strength of VR lies in the fact that it can immerse the user in a simulated environment that may or may not be available in the real world. In addition, VR provides enough control to the developers of those experiences to create content that can evoke specific emotions. For example, horror games can make players feel scared [15, 17], and an immersive funny cartoon movie may make viewers feel happy [5].

There have been some previous efforts at using VR experiences for evoking and measuring emotions. However, the effect of showing the user his or her *own* emotional state in a VR environment has not extensively researched. Recently Dey et al. [7] reported on one of the first experiments where the heart rate of a remote collaborator was displayed to a VR user to make the collaboration more empathetic. However, in that work the authors only used a single type of audio-visual feedback to display the heart rate.

There is a need to understand how to represent physiological states for maximum effect, which will enable VR researchers to create more empathetic VR experiences. By making VR systems more empathetic they can be used for various training and teaching purposes [12]. An empathetic VR system can also help treating phobias and disorders [11]. This paper primarily focuses on that aspect. We systematically measured the real-time heart rate of VR users and presented it using four different multi-sensory combinations. While the benefits of multi-sensory feedback of general interactions in VR has been established by earlier work [10], that effect has not been studied adequately for providing physiological feedback. The primary contribution of this paper is the thorough rigorous user study investigating the effects of multi-sensory heart rate feedback. We found that visualizing users own physiological state enhances the VR experience and that audio-haptic feedback is the preferred mode of heart rate representation in VR.

The rest of the paper is organized as follows. In Section 2, we discuss earlier research in this direction and how our current work fits within the context. Next, in Section 3 we discuss the VR experiences we developed and the apparatus used in creating the testing scenarios. The following section, describes the user evaluation in detail and Section 5 reports on the outcome of the study. Then we discuss the results and how they address the research goal in Section 6. In Section 7, we conclude by pointing towards future research directions.

2 RELATED WORK

Emotions acting as ubiquitous affective states in the social and behavioural world have been researched in virtual environments (VEs). Several researchers have hypothesized that the emotions elicited in the real world could be provoked by the corresponding virtual environment [1, 8, 9, 20]. A series of investigations in VEs has been conducted, including whether the same virtual park with different emotional triggers would provoke the target emotions (Felnhofer et al. 2015).

Virtual Reality has been able to evoke emotions in users. For example Riva et al. [20] created two emotional virtual environments (relaxing and anxious virtual parks) and a neutral virtual environment as a control condition. The three VEs had the same virtual objects, including a tree, summer cinema, lamps and bandstand, but the sound and music, shadows, lights and textures were varied to create different emotional experiences. Subjectively, the researchers showed that after the exposure to the anxious VE, the user's feeling of happiness and positive affect was reduced and sadness and anxiety was increased and in the relaxing condition, the direction was the opposite, while the neutral one had no significant changes. Later this research was expanded into five emotions, including sadness, joy, boredom, anger and anxiety [9]. Objective (electro-dermal activity) and subjective measurements were utilized in the study. Four of the five emotional scenes could evoke the target emotions from the subjective analysis, while the objective measures did not change significantly between the scenes.

In the project EMMA, Raya et al. studied whether emotions could be induced in VR users in response to the positive and negative mediated experiences [19]. Based on the framework of EMMA project, five emotions, such as sadness, joy, anxiety, relaxation and naturalness, were involved in a VR evaluation [2]. From the post-hoc analysis, they showed that the happiness and relaxation VEs scored higher in joy mood, followed by the neutral one, than anxiety and sadness groups. However, the anxiety and sadness VEs induced a sadder mood than the happiness, relaxation and neutral VEs. Banos et al. conducted another study to investigate whether elderly people would have increased positive emotions after exposure to positive emotional VEs [2]. In the user study, two emotional virtual parks (relaxation and joy) were designed. They found that participants' positive emotion was increased and negative emotions were reduced after being exposed to the two positive VEs.

Similarly, Seinfeld et al. [21] designed a VE with an exterior elevator in a 350m building to evoke anxiety in ascending and descending. They compared the user response in this VE to a baseline VE showing a terrace with tables and chairs. In the study when the simulated elevator ascended, the subjective and objective results of emotion were significantly different compared to the situation on the ground. The higher the floor the participant was taken to, the more significant the difference. That means the participants in higher floors were more anxious. Overall, these sets of studies show that VR is capable of creating emotions akin to real world scenarios in a single user VR experience.

There are also few recent examples of works that focus on collaborative VR environments and provide physiological feedback. For example Dey et al. [7] in a virtual shooting game aimed to share the emotional states between the player and the viewer (a less-active participant in the game). This research explored how to use a shared viewpoint and simple empathetic cues to increase the feeling of connection and to enhance the experience in a collaborative VR environment. The heart rate of the player was visualized using only audio-visual channels to the observer. The study found benefits of sharing physiological cues in terms of increased subjective connection and positive affect.
Bernal and Maes [3] developed a system to express emotions using avatars in a virtual environment. User's Galvanic Skin Response (GSR) and heart rate (HR) physiological signals were captured and a neural network was used to estimate four emotions from the raw GSR and HR data. They represented emotions visually in two different ways: (1) the fur in the skin of avatar (grows when the arousal is high) and (2) intensify the brightness or to change colour to highlight the avatar when the user is in high arousal situation. The system was designed using an open source VR system called PhysioVR [16]. Apart from this no other work has focused on investigating different modes of visualizing physiological data to help the users understand it better.

In our work, we compare four multi-sensory visualizations of heart rate data in an immersive VE utilizing audio, visual, and haptic feedback. The main novel contributions of our research are: a rigorous systematic comparison of four multisensory feedbacks of heart rate, and a design guideline for providing such feedback in future VR systems.

3 VIRTUAL REALITY EXPERIENCES

For our study, we developed five different VR test experiences using the Unity 3D game engine. Each of the environments was

Figure 1: In each of the VR environments we designed five different emotions experiences of same length. The experiences were: happiness (a), anxiety (b), fear (c), disgust (d), and sadness (e). A full view of the visual heart rate feedback is shown in (a).

carefully designed and validated to evoke similar experiences in the same order and for equal amounts of time. We primarily focused on five different emotions––happiness, anxiety, fear, disgust, and sadness (Figure 1). They are in one VR scene. Taking one VR scenes for example, the fear part has a dinosaur attacking the pickup and yelling towards to the user. The sad part has a wolf lost his mother and was walking around his mother with mourning sound. The disgusting part has the scene where were rotten animal's bodies and blood littered along the road. The happiness part has butterflies were flying around the pickup and beautiful flowers, green grass and trees were in the scene as well. The anxiety part has lions attacking another pickup and the driver was crying for help. Each of the sections lasted for 45 seconds and the whole experience lasted for approximately four minutes. A transitional five-second black screen was shown between each segment of the experience.

3.1 The Design of the Experiences

The VR experiences were based on a jungle safari with various animals (including dinosaurs) moving through in the environment and supplemented with appropriate sound effects. The player was placed on the back of a virtual car, which moved on its own without any intervention from the player. In the real world, the player was standing with a hand-rest in front to maintain balance, if needed. The user was allowed to look around and rotate his/her head to experience the VR environment at will. However, s/he

Figure 2: Participants were wearing a HTC Vive display, Logitech Headphones, and Polar H7 heart rate sensor.

was not allowed to walk.

We conducted pilot studies to make sure that the environments triggered different appropriately perceived emotions by participants, and executed different events that triggered the experiences. For example, to trigger happiness we showed a waterfall and many butterflies flying around, while for fear, we presented roaring panthers and dinosaurs.

Most of the visual effects of interest were presented in front of the users' eyes within 200^{O} horizontal field of view. However, there were sound effects that originated behind the users.

3.2 Apparatus Used

The VR environment was experienced through an HTC Vive headset [13] and the sound was delivered through Logitech headphones (Figure 2). The Vive display was equipped with a Pupil Labs eye-tracker [14] to measure the pupil dilation of the user while experiencing the VR environments. The user was asked to stand and hold the Vive controllers in both of her hands, and wore a Polar H7 heart rate sensor [18].

4 USER STUDY

We designed and ran an one-way, within-subjects user study to evaluate the effects of different ways of displaying the heart rate signal on the user's understanding of his/her own physiological state and the environment. In this section, we provide a detailed description of the user study design.

4.1 Independent Variable

The independent variable was the *Multi-Sensory Heart Rate Feedback* with five different conditions; (1) None, (2) Audio-Visual, (3) Visio-Haptic, (4) Audio-Haptic, and (5) Audio-Visual-Haptic.

To visualize the heart rate information to the participant, we adopted a multi-sensory approach, particularly focusing on the audio, visual, and haptic senses. Visual feedback was given by displaying a red heart symbol on the screen, which changed its size proportionately to the change in heart rate. The auditory feedback was provided by the sound of a heartbeat played back through the Logitech noise-cancelling headphone. We adjusted the volume level of the headphone to the comfort level of the participants. The haptic feedback was provided as vibrations through the handheld Vive controllers. The vibrations were synchronized with the participant's real-time heart rate. In one condition (None), we did not provide any feedback, as a baseline case. In three conditions, we coupled two of the three senses, and in the fifth condition we displayed feedback through all senses together.

We counterbalanced the order of the feedback and environments using a 5x5 balanced Latin-square design, which enabled each environment to be experienced using different multi-sensory feedback an equal number of times.

4.2 Dependent Variable

We were mainly interested in subjective preferences of heart rate feedback types. Hence, we primarily focus on qualitative data. We administered a Positive And Negative Affect Schedule (PANAS) scale [25], a Self-Assessment Manikin (SAM) questionnaire [4], and a subjective preference questionnaire that included ranking of the multi-sensory feedback types (Table 1). In the end, we performed a short semi-structured interview with each of the participants. As quantitative variables, we measured the participants' real-time heart rate and pupil dilation during the experiences, and their head orientation during the task.

4.3 Experimental Task

The task was simply to experience the immersive VR environments using HTC Vive while leaning on a swivel chair and holding the controllers. We asked participants to stand throughout the experiment to reduce their physical movement, which could have confounded the experiment by increasing heart rate. To maintain consistency among all conditions, we asked participants to hold the controllers even when haptic feedback was not given. First we explained the experiment to the participants, followed by signing of the consent forms and demographic data collection. We asked participants to relax for two minutes before starting the experiment. Then we collected baseline data for two minutes in a standing position without wearing any VR gear. Following the baseline data collection, we showed a peaceful demo VR environment to the participants for a minute, which enabled participants to get used to VR and reduce the "wow-factor" before the experiment. After that, participants were asked to relax for another minute before starting the main experiment.

Following the baseline heart rate data collection, participants started the first VR experience. Then the participants answered the subjective questions. This process was repeated five times in the whole experiment. After all five experiences, we interviewed the participants. Participants were asked to take a break between each experience for as long as they wanted after completing the questionnaires. For each participant, the whole experiment took about 60 minutes on average.

4.4 Participants

We recruited a total of 20 participants (five female), with ages ranging from 22 to 58 years (M=31.65). Participants were recruited from the university students and staff and personal contacts of the authors. Nineteen participants had computer gaming experience and only nine participants had experience with VR. Fourteen participants reported that they normally did not pay attention to their heart rate in daily life. None of the participants had any visual or auditory impairment.

Overall, the study included 5 (feedback) X 20 (participants) = 100 data points. This resulted in a statistical power of greater than 0.8 for the repeated measures ANOVAs we used in our analysis.

4.5 Hypotheses

At the outset of the experiment, we had the following hypotheses.

H1 The Audio-Visio-Haptic condition will be subjectively preferred significantly more and have the highest ranking of any condition, as this condition provides feedback through highest number of modalities.

H2 The Audio-Visio-Haptic condition will create significantly more positive effects than all other conditions.

Survey Questions		Scale	
		1	5
Q1	How much attention did you pay to your heart rate when in the game?	Very inattentive	Very attentive
Q2	How much did you feel your heart rate when in the game?	Very less	Very much
Q3	How much do you agree that you understood your heart rate accurately through the visualization?	Very much disagree	Very much agree
Q4	How much did the heart rate visualization add to enhance the enjoyment when in the game?	Very less	Very much
Q5	How much do you agree that the heart rate visualization distracted your experience when in the game?	Very much disagree	Very much agree
Q6	Please rank the conditions according to your preference	Best	Worst

Table 1: Subjective questions asked after each session in the experiment, except for Q6, which was asked only once at the end of all sessions.

H3 In general, conditions with visual feedback will receive lower preferences than conditions without visual feedback as visual feedback may add distractions.

H4 The baseline (None) condition will have significantly worse subjective preferences, as it does not provide any heart rate feedback.

5 RESULTS

Overall we found that participants preferred to have heart rate feedback as all conditions with feedback were subjectively rated better than the None condition. Haptic-Audio condition was found to be most preferred.

To analyse the data, we used SPSS v.21. To analyse the subjective data, we used non-parametric tests, and for objective data we used repeated-measures ANOVA followed by a post-hoc test with Bonferroni's adjustments.

Conditions	Ranking	Q1	Q2	Q3	Q4	Q5
Baseline (None)	3.7 (1.7)	1.6 (1.0)	1.6 (0.9)	1.6 (1.0)	1.3 (0.6)	1.6 (1.3)
Audio-Visual	3.2 (0.9)	3.7 (0.9)	3.2 (1.1)	3.5 (1.1)	2.9 (1.0)	3.1 (1.3)
Visio-Haptic	3.4 (1.1)	3.5 (1.1)	3.2 (1.2)	3.2 (1.0)	3.1 (1.1)	3.1 (0.9)
Audio Haptic	2.2 (1.3)	3.0 (1.2)	3.5 (1.1)	3.5 (0.9)	3.2 (1.1)	2.4 (1.0)
Audio-Visual-Haptic	2.6 (1.5)	3.6 (1.2)	3.8 (0.8)	3.7 (0.9)	3.1 (1.0)	2.9 (1.1)

Table 2: Mean (standard deviation) of ranking and subjective questions.

Conditions	Positive Affect	Negative Affect	Valance	Arousal	Dominance
Baseline (None)	28.2 (5.1)	19.5 (7.2)	2.9 (1.0)	2.8 (1.0)	2.6 (0.9)
Audio-Visual	27.9 (5.7)	20.8 (7.8)	2.7 (0.9)	2.8 (0.8)	2.5 (1.0)
Visio-Haptic	27.7 (6.2)	20.7 (6.5)	3.0 (0.8)	2.7 (0.8)	2.7 (0.9)
Audio Haptic	27.0 (6.3)	19.1 (7.5)	2.9 (1.1)	3.1 (0.8)	2.5 (0.9)
Audio-Visual-Haptic	29.6 (5.2)	20.0 (6.6)	2.5 (1.1)	2.9 (1.1)	2.6 (0.9)

Table 3: Mean (standard deviation) of PANAS and SAM questionnaires.

5.1 Ranking

We analysed ranking data using a Friedman test and Wilcoxon signed-rank post-hoc tests. Overall, the **Audio-Haptic** condition was ranked the best and the baseline **None** condition was ranked the worst. A Freidman test showed an overall significant effect of conditions on ranking - χ^2 (4) = 12.12, p = 0.016. A follow-up Wilcoxon signed-rank test revealed that the **Audio-Haptic** condition was significantly better than **None** (Z = -2.67, p = .007), **Audio-Visual** (Z = -2.05, p = .041), and **Visual-Haptic** (Z = -2.35, p = .019). The **Audio-Visual-Haptic** showed a trend towards having a better rank (Z = -1.84, p = .065) than the **None** condition. This ranking data (Table 1) clearly indicates that the participants preferred to have heart rate feedback during their gaming experience; in particular they preferred Audio-Haptic feedback.

5.2 Questionnaire

We asked participants to respond to a 5-point Likert-scale based questionnaire to report their feedback on the following aspects. For each of the questions, we ran a repeated measure ANOVA and a post hoc analysis with Bonferroni's adjustments. Overall, the baseline (None) was found to be less favourable to participants, although it caused least distraction in the experience. Hence, the value of adding physiological feedback in VR experiences is established. Below we present the analysis in detail.

Q1. How much attention did you pay to your heart rate when in the game?

Analysis showed that participants paid significantly less attention to their heart rate in the baseline (None) condition than all other conditions F(4,76) = 13.44, p < .001, η_p^2 = .41, observed power = 1.0. A post-hoc test showed that in the baseline (None) condition, participants were significantly less attentive to their heart rate.

Q2. How much did you feel your heart rate when in the game?

We found, using ANOVA and post hoc tests, that participants felt their heart rate significantly less in the baseline (None) condition than all other conditions F(4,76) = 19.04, p < .001, η_p^2 = .5, observed power = 1.0.

Q3. How much do you agree that you understood your heart rate accurately through the visualization?

Similarly, the baseline (None) condition made participants significantly less understanding of their heart rate during the experiences than all other conditions F(4,76) = 14.91, p < .001, η_p^2 = .5, observed power = 1.0.

Q4. How much did the heart rate visualization add to enhance the enjoyment when in the game?

Understandably, the baseline (None) condition added least to enhancing the enjoyment than all other conditions F(4,76) = 14.91, p < .001, η_p^2 = .5, observed power = 1.0.

Q5. How much do you agree that the heart rate visualization distracted your experience when in the game?

On a positive note, baseline (None) condition was significantly least distracting than all other conditions F(4,76) = 14.91, p < .001, η_p^2 = .5, observed power = 1.0. However, this is understandable, as the baseline condition did not provide any additional feedback.

5.3 Positive and Negative Affect Schedule (PANAS)

The Positive And Negative Affect Schedule is a measure of overall positive and negative effects in a given experience measured through 20 different emotions and feelings [6]. Overall, there was more positive affect than negative affect in all conditions. However, we didn't notice any significant effect of conditions on either positive affect F(4,76) = 1.79, p = .14, η_p^2 = .1; or negative affect F(4,76) = 1.07, p = .38, η_p^2 = .05 (Table 3).

5.4 Self-Assessment Manikin (SAM)

We measured Valance, Arousal, and Dominance using the SAM questionnaire. However, we did not notice any significant differences between the conditions in terms of valance, arousal, or dominance (Table 3).

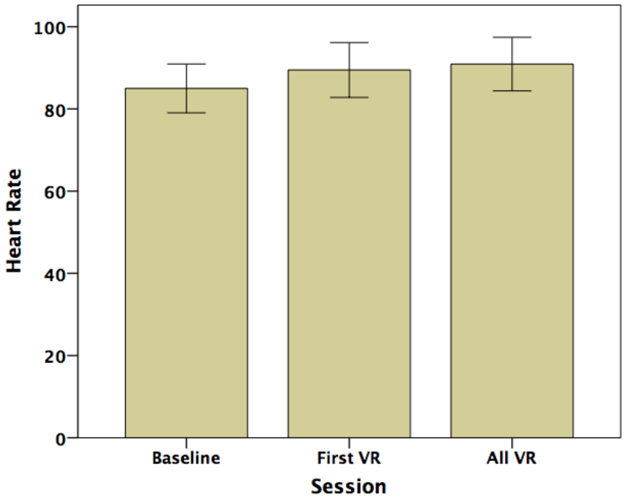

Figure 3: Heart rate at baseline was significantly less than heart rate in VR sessions. Whiskers represent +- 95% confidence intervals.

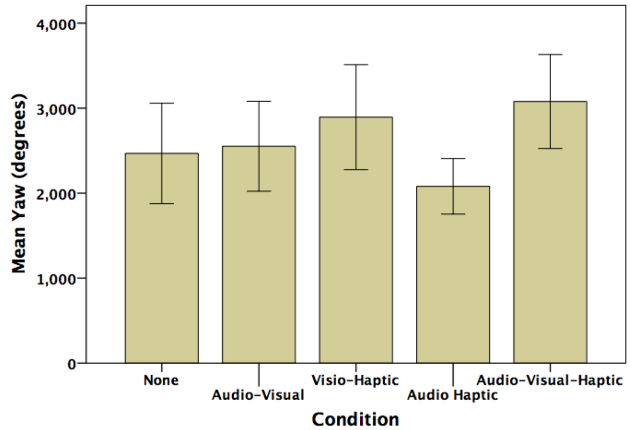

Figure 4: Yaw (horizontal head movement) was significantly more in the Audio-Visual-Haptic condition than in the Audio-Haptic condition. Whiskers represent +- 95% confidence intervals.

5.5 Semi-Structured Interview

After all the experimental sessions were completed, we asked participants about their opinions on the heart rate feedback methods and the VR environments. All the participants reported that they enjoyed the environments and felt different experiences within each environment, as we initially wanted them to. For example, P10 said *"I thought it will be a pleasing safari as it started in the beginning but as the car took me through the jungle I started to feel different."* P17 mentioned, *"I felt sad for the poor wolf* (Figure 1e) *who just lost his mother."* Except for one, all participants reported that the visual feedback was distracting and reduced the enjoyment of the safari to some extent. Out of 20, 17 participants reported that the audio feedback was most important for them and helped them the most to understand their heart rate. Among the remaining three participants, two participants preferred the haptic feedback and one preferred visual feedback. A couple of participants who reported the visual feedback to be distracting reported that they got used to the effect afterwards and were able to focus on the VR environment more over time. In terms of ranking, most of the participants preferred Audio-Haptic feedback among the five types of feedback.

In terms of the VR environment, participants wanted more interaction. For example, one participant (P4) wanted to be able to pat animals and another participant (P9) wanted to touch trees. Among the scary effects, five participants reported the human screaming was the most frightening effect.

5.6 Heart Rate

We measured participants' heart rate while they were experiencing the game. We were particularly interested to investigate whether being in VR increases their heart rate from not being in VR and also whether there was any effect of the conditions on average heart rate.

To analyse the effect of VR on heart rate, we compared the mean baseline heart rate with the mean of all VR session heart rates using a one-tailed paired t-test. We found that being in VR significantly increased participants' heart rate: $t(19) = -2.21$, $p=.02$. We also noticed a close to significant increase in heart rate when we compared the mean baseline heart rate with mean heart rate of the first VR session for each participant: $t(19) = -1.54$, $p=.07$ (Figure 3). However, when compared the mean heart rates in different conditions using a repeated measure ANOVA we did not notice any significant difference. Similarly, we did not notice any significant difference when we compared heart rate variability (change from baseline heart rate).

5.7 Head Movement

As an indication of how much participants looked around the VR environment in each condition we measured their angular head movement in terms of both yaw (horizontal movement) and pitch (vertical movement). The data was collected as an angular distance between their head orientation at every second during the VR sessions.

We noticed that yaw was significantly affected by the conditions $F(4,76) = 4.41$, $p = .003$, $\eta_p^2 = .18$. A post-hoc test showed that **Audio-Visual-Haptic** (M= 3078.41, SD = 1182.15) condition had significantly more yaw than the **Audio-Haptic** (M=2080.16, SD = 698.23) condition (Figure 4). The reason for this effect is unclear. Probably, not having a visual heart rate feedback made participants get most of the environment without moving their head too much as the visual distraction was missing. However, we didn't notice any significant difference between the conditions in the case of pitch.

5.8 Pupil Dilation

We also measured the diameter of the pupil of the right eye during the task using Pupil Labs eye tracker. First, we measured dilation at baseline by systematically varying brightness of the scene displayed through the HTC Vive display. Then during the experimental tasks, we measured the dilation. As different environments had different average brightness, to analyse the data we normalized the dilation to 100 cd (candela) and measured the change in dilation as a ratio to the baseline data. However, we did not notice any significant difference between the conditions. Although, while being in VR (M=41.93, SD=9.7) normalized pupil diameter increased slightly than in baseline (M=38.59, SD=13.1) however, the difference was not significant.

6 DISCUSSIONS

Providing physiological feedback to users in a VR environment can make the user more aware of his/her own emotional state and in a collaborative setup it can help collaborators understand each other [22]. In this work, we focused on a single user experience and provided heart rate feedback using combinations of visual, audio, and haptic modalities.

We postulated four hypotheses at the beginning of the study. We expected the **Audio-Visual-Haptic** condition would create the highest positive affect and would be most preferred by the participants. This was because **Audio-Visual-Haptic** condition provides the feedback through most number of channels and it will help participants feel their heart rate the most. However, these two hypotheses were not accepted in the user study. On the contrary, **Audio-Haptic** feedback was most preferred and visual feedback was labelled as distracting by most participants. This makes sense as our visual feedback was a large red heart symbol changing its size based on heart rate increase or decrease proportionally, which acted as a pre-emptive cue in the environment and attracted user attention most of the time; even when it was not desired. This was also a reason for the partial acceptance of our Hypothesis 3, that we expected conditions with visual feedback would have less preference than conditions without visual feedback.

Our final hypotheses, that postulated the **None** condition would have the worst preference was accepted as subjectively it was ranked and rated the worst. This is a clear indication that participants appreciated getting their own heart rate feedback and so future VR interfaces may consider including appropriate visualization of physiological data in the experience.

We noticed that there was no significant difference in terms of PANAS and SAM scores in any of their subscales. We believe VR experiences we used in the experiment were not long enough and we did not provide any interaction opportunities beyond just looking around. Also if we increased the fidelity of the VR graphical elements the participants could have increased emotional arousal [24].

Overall, as far as the design space is concerned, through our initial exploration of the multisensory visualizations, we argue that audio feedback is most suitable for providing heart rate feedback and seems to have the greatest effect on the users. First, this modality does not affect the visual experience of the VR environment and second, users are used to listening to heartbeat sounds, which enables them to comprehend the heart rate information more through audio feedback than any other feedback. One participant (P5) said, " ... it feels natural [to hear heartbeat]." Some participants also preferred haptic feedback than visual feedback. We believe haptic feedback is a more natural way of perceiving heart rate than visual as in real life humans can feel their pulse through haptic feedback. Usually there is no way for humans to see their heartbeat in natural environments, so we believe audio and haptic feedbacks are most suitable and natural modalities for heart rate representation in a VR environment.

6.1 Design guidelines

Overall, based on this study, we believe a VR system can increase the overall experience of user by following these design guidelines: (1) the system should provide feedback of physiological data such as heart rate; (2) if possible, the feedback should be provided primarily through audio and haptic channels, keeping the visual space free for the VR environment; and (3) even in an exploratory VR environment, some interactions with the environment can increase engagement.

6.2 Limitations

In this paper, we have performed a rigorous user study with customized experimental VR environments. However, the study has a few limitations. First, we only considered an exploratory VR environment. There are several other environments that involve more active participation and interaction by the user, which we did not include in the study. Second, we have used only heart rate feedback in this study. However, there are other physiological measures that we could have used in the experiment but did not such as galvanic skin response (GSR) and respiration rate. However, these limitations could be studied in future dedicated experiments.

7 CONCLUSIONS AND FUTURE WORK

In this paper, we have presented four different multi-sensory visualizations of heart rate data in immersive VR experiences. The goal was to explore the multi-sensory design space for providing feedback of physiological data to a user in an attempt to make them feel their physiological state to make the experience more immersive and empathetic. This is the first time these types of heart rate representations have been compared in a VR environment, and it is important because knowing one's physiological state can make a person self-aware and in a collaborative setup make the collaborators empathize with each other.

We performed a thorough within-subjects user study with 20 participants and found that providing feedback of heart rate enhanced the user enjoyment more than not providing it at all. Participants especially preferred the **Audio-Haptic** condition and they found the visual feedback distracting. Most of them reported the audio feedback to be most helpful. We conclude that, when possible, physiological feedback should be provided to the users in VR experiences to increase their enjoyment. For visualizing physiological data, particularly heart rate, VR experience designers should use audio-haptic feedbacks and keep visual space dedicated for the core VR experiences.

In the future, we would like to explore the effects of visualizing physiological states of users in collaborative VR systems. In this paper, we focused on multi-sensory feedback. We would like to explore the effects of individual feedback such as audio or haptic feedback by itself. It would also be interesting to investigate whether providing different heart rate feedback can influence a user's real heart rate [23]. For example, if hearing a fast-exciting heartbeat will make them feel more excited. We will also explore how multiple physiological feedbacks such as heart rate and GSR together, can be provided in the same environment using multi-sensory feedback. It will also be interesting to perform a similar study in an environment where more interactions are required such as a VR shooting game. Overall there are a number of very interesting ways that this research could be extended in the future.

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