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Exploring Pupil Dilation in Emotional Virtual Reality Environments

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(A) Happiness (B) Anxiety (C) Fear

(D) Disgust (E) Sadness

Figure 1: *In each of the VR environments we designed five different emotions experiences of around 4 minutes length. The experiences were: happiness (a), anxiety (b), fear (c), disgust (d), and sadness (e).*

Abstract

Previous investigations have shown that pupil dilation can be affected by emotive pictures, audio clips, and videos. In this paper, we explore how emotive Virtual Reality (VR) content can also cause pupil dilation. VR has been shown to be able to evoke negative and positive arousal in users when they are immersed in different virtual scenes. In our research, VR scenes were used as emotional triggers. Five emotional VR scenes were designed in our study and each scene had five emotion segments; happiness, fear, anxiety, sadness, and disgust. When participants experienced the VR scenes, their pupil dilation and the brightness in the headset were captured. We found that both the negative and positive emotion segments produced pupil dilation in the VR environments. We also explored the effect of showing heart beat cues to the users, and if this could cause difference in pupil dilation. In our study, three different heart beat cues were shown to users using a combination of three channels; haptic, audio, and visual. The results showed that the haptic-visual cue caused the most significant pupil dilation change from the baseline.

CCS Concepts

***•Computing methodologies** → **Virtual reality; •Human-centered computing** → Empirical studies in HCI;*

1. Introduction

In this paper we explore pupil dilation behaviour in response to Virtual Reality experiences designed to create an emotional response. In many Virtual Reality (VR) experiences it may be important to measure the user's emotional response. For example, in a VR game, the developers may want to know if the experience is exciting enough, or an artist may want to create a VR art piece that makes

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people feel happy. Currently, the most popular way to investigate emotions is to use subjective questionnaires, such as Positive and Negative Affect Schedule (PANAS) [WCT88], Self-Assessment Manikin (SAM) [BL94], and Differential Emotions Scale [Iza93]. However, Emotion is also manifest through the autonomous nervous system which controls changes in physiological cues such as skin conductance, facial expression, heart rate, body temperature, and pupil dilation, among others [BG12, PS03, KTN13].

In our research we are exploring pupil dilation response to different types of VR experiences, to see if this can be used as a reliable measure of emotional response. Measuring pupil dilation has several advantages compared to other physiological measurements. Pupil dilation can be measured by unobtrusive eye tracking hardware and there are no sensors or electrodes that need to be attached to the user. Pupil size variation is an involuntary index of autonomic nervous system (ANS) activity and so cannot be voluntarily controlled [PS03]. This means that pupil dilation identifies real spontaneous activity and so could be a reliable physiological measure. In contrast, when using facial expression for emotion recognition, the visual observable changes in facial emotional behavior can be masked, inhibited, exaggerated, and faked. A trained actor can easily mimic a variety of emotional face expressions.

Pupil dilation has been studied for many years, and automatically occurs depending on the amount of light entering the eye. However, pupil dilation can also be changed by the person's cognitive load, mental imagery effects, and various forms of stimuli, such as images and sounds [Mar00, KTN13, BG12]. In our system, five immersive VR environments were used to evoke emotions. Each environment was designed to create five emotions —happiness, fear, disgust, sadness, and anxiety. In addition to showing users the VR environments, we also added feedback of their real-time heart rate using a combination of haptic, audio, and visual channels. This was designed to increase the emotional influence of the VR scenes. Overall, we found that the negative and positive emotional segments in the VR environments both increased the pupil dilation in users.

The main contribution of this work is that it is one of the first times that pupil dilation has been systematically studied for a range of different VR experiences. We also describe a novel way of measuring the pupil dilation due to the VR content rather than just the brightness of the display. Finally, the method that we have developed could be used to give an objective measure of emotional response to VR environments.

In the remainder of the paper we first review related work in Section 2, and then Section 3 describes our prototype system for measuring pupil dilation in a VR environment. Next we discuss the exploratory study we conducted in Section 4, and the result found from the study in Section 5. Finally, in Section 6 we give a discussion of the results and we conclude by directing towards for future work in Section 7.

2. Related Work

Research into pupil dilation and constriction in response to light stretches back at least 100 years with the pioneering work of Reeves [Ree18] who explored the response of one or both eyes to different amounts of brightness. He found that the pupil diameter responds differently for each individual, but the response function has the same characteristic shape. This effect has been confirmed by many researchers in the years since, such as [BP39] and [YB54]. In the context of Virtual Reality this means that when a person is wearing a VR head mounted display (HMD) their pupil diameter will change relative to the amount of light entering their eyes from the HMD.

Going beyond responding to light, pupil dilation also occurs in response to emotional arousal and other factors. Research into pupil dilation as an indication of negative and positive arousal has been investigated for many years. For example, Hess et al. [HP60] famously reported that the pupils constricted when people viewed unpleasant pictures and dilated when they viewed pleasant pictures. However researchers after him found that emotional arousal modulated the pupil dilation by increasing the pupil diameters. Bradley suggested that Hess' work had some methodological difficulties [BMEL08]. In his study he used more pictures and participants and all the stimuli pictures were from International Affective Picture System [LBC99]. The results showed that both negative and positive arousal pictures enlarged the pupil diameters in users, compared to neutral pictures. Kawai et al. [KTN13] also investigated pupil diameter variation by using visual stimuli with positive and negative images and they found the pupil diameter in the positive emotion was smaller than that in the negative emotion.

Similarly, Partala et al. [PS03] found that when subjects were listening to the different emotionally arousing audio clips the pupil size was significantly larger during both emotionally negative and positive stimuli than during neutral stimuli. In this case they used the audio sound stimuli set called the International Affective Digitized Sounds (IADS) designed by Bradley and Lang [BL91] to create an emotional response to audio. Audio storytelling with emotional content [BG12] and even pure audio tones [WBM12] have been shown to create pupil dilation.

From the story telling research [BG12], when the participant listened to the negative arousing story, the pupil dilation would be significantly larger than that in a neutral story. The pupil dilation also changed when the audio was switched from the music to a talk. Baltaci et al. found that the single and female subjects were the most sensitive participants in the study.

These studies show that pupil dilation and diameter changes occurs in response to emotionally arousing visual and audio content. However, although pupil dilation has been studied in many different domains, there has been little or no work studying it in VR. This is due to many factors including the difficulty of getting access to eye-tracking hardware suitable for VR displays, proper emotional arousal scenes, and the difficulty in separating effects of emotions, brightness, and interaction on pupil dilation. In the next section we provide a brief overview of previous work in measuring emotion in VR.

2.1. Emotions in VR

In psychology, videos and pictures have been shown to induce an emotional response [LNR96, BCL96]. Similarly, studies have

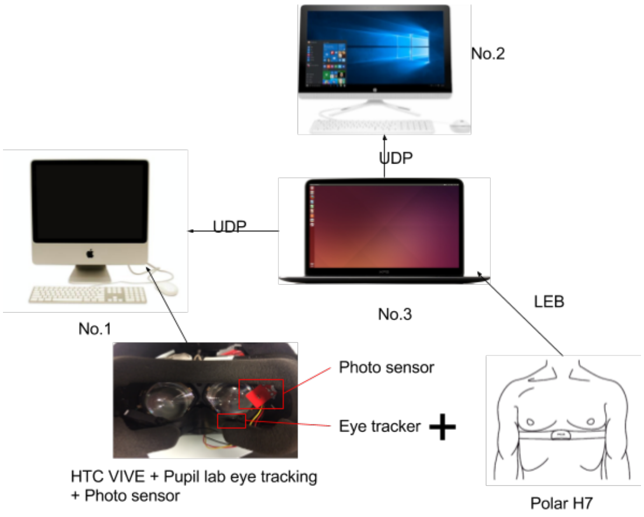

Figure 2: *System Overview.*

shown that VR can elicit emotions [RMC*07, AF10]. For example, Riva et al. [RMC*07] used three virtual environments (anxious and relaxing parks) randomized for participants, and these induced anxiety and relaxation emotions. Meehan et al. [MRI*05] say that at least three things are required when incorporating a particular physiological measure into a VE; (1) the use of virtual environments that evoke physiological responses, (2) distinguishable physiological responses to VEs, and (3) consistent measurement of physiological reaction in the general population.

Herrero et al. [HGPC*14] created a VR environment to evoke positive emotion to treat fibromyalgia and reported positive impact. In a recent review, Diemer et al. reported that emotion has little impact on Presence in VR environments. They have also highlighted that fear and anxiety are the two emotions that are well studied using VR [DAP*15]. There are other examples of recent work that has used VR to trigger emotions in a serious setting such as treating paranoia [AAE*16], PTSD [RCG*15], and stroke rehabilitation [SPJ15]. A recent review has reported that behavioral gains achieved though VR therapies are transferred into real life, which shows the effectiveness of VR for treatment of emotional disorders [MIME15].

This research shows that VR can be used to create powerful emotional experiences. Some researchers have used physiological cues to measure user's response to these experiences. For example, Meehan et al. [MRI*05] measured user's heart rate to identify their level of fear in response to a virtual pit experiment. However, none of these VR systems have measured pupil dilation and used that as an indicator of the user's emotional state. In the next section we describe the prototype system that we developed to measure pupil diameter and the VR setup.

3. Experimental System

To measure user's physiological response to a VR experience we developed the system shown in Figure 2. This combined input from an eye-tracker and the user's heart rate in response to visual and audio cues created in a VR environment. To run the prototype software and hardware there were three computers used. One is an iMac, labeled as No.1, one is a desktop computer with the Windows 10 operating system, labeled as No.2, and the last one is a laptop, running Ubuntu Linux, labeled as No.3.

Eye-tracking and measurement of the pupil diameter was performed on the iMac. This computer was running the Pupil Labs open source eye tracking software [Pup], which captures the pupil dilation. This software works with the Pupil Lab eye tracking hardware integrated into the HTC Vive head mounted display (HMD). Figure 3 shows the HTC Vive HMD with the integrated Pupils Labs eye-tracker. The Pupil Labs HTC eye-tracker tracks the eye gaze at 120 Hz with an accuracy of 0.6 degree, and can measure the pupil diameter to an accuracy of 1 mm.

In addition, a custom photo sensor was mounted beside the eye tracking camera in the HTC Vive. This photo sensor was used to measure the light emitting from the HMD display elements. In this way the VR scene brightness and the pupil dilation were both captured when the headset was worn by users. The photo sensor in our user study is a Light Dependent Resistor [Pho], connected to an Arduino board as shown in Figure 4. The range of data from Arduino is from 0 to 1023, where 0 indicates the minimum brightness while 1023 indicates the maximum. The Arduino board was connected via USB to the Windows computer.

The sample VR applications were run on Computer No.2. All of the VR scenes were built and designed in the Unity game engine [Uni], and provided the visual and audio cues experienced by the user. The HTC Vive HMD was connected to this computer, as well as the Lighthouse tracking system used to measure the user's head position. The user also held the HTC Vive handheld controllers in their hands, that were used to provide haptic cues through vibration.

The final element of the system was heart rate recording that was measured by the No.3 computer. In this case the computer communicated with a Polar H7 heart rate (HR) sensor worn by the user [Pol]. The Polar H7 measures heart rate. In our user study, the sampling rate of the data streamed from the Polar H7 was once per second.

The Generic Attribute Profile was used to connect the No.3 com-

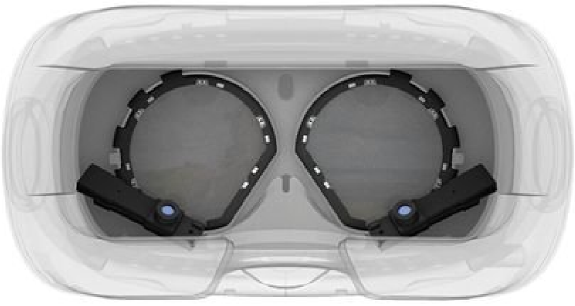

Figure 3: *Pupil labs eye tracker for HTC VIVE.*

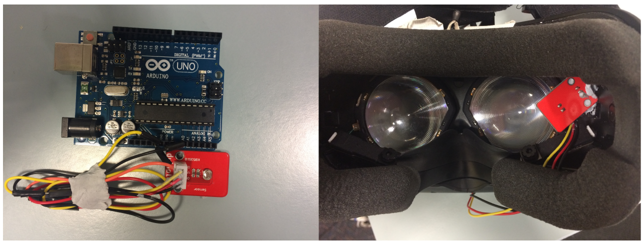

Figure 4: *Left:Photo sensor and Arduino Board. Right: The photo sensor and eye tracker in HTC Vive HMD.*

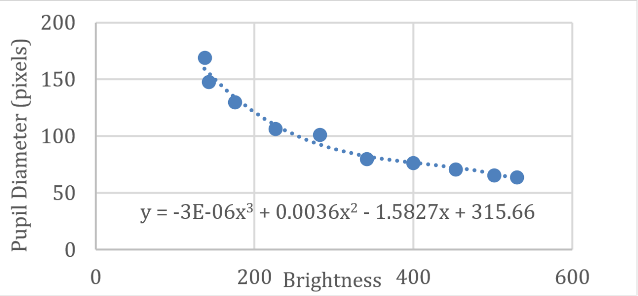

Figure 5: *Relationship between brightness and pupil dilation.*

puter and the Polar H7, enabling the Polar H7 HR data to be streamed to No.3. Then the data was transferred to computer No.2, using the UDP protocol, where the HR data was visualized and presented to the user, using a variety of audio and visual cues in the VR scenes and haptic cues on HTC Vive controllers. Finally, in computer No.1, the HR data was paired and synchronized with the pupil dilation data.

The overall outcome of using this system is that we were able to show a variety of VR experiences to a user, and then measure the user's heart rate response, and their pupil diameter changes. This provides an ideal platform for us to conduct the user study described in the next section.

4. Exploratory Study

Using the prototype system an exploratory study was conducted to measure pupil dilation response to different VR experiences. In this system heart rate feedback was provided using a combination of different audio, visual, and haptic channels. The default VR scene used was of a virtual African safari with grasslands, scrub and a variety of animals as shown in Figure 1. At different segments in the scene users experienced difference content designed to create an emotional response.

In our user study, we provided multi-sensory heart rate feedback to participants, 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 a 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 combining all of the senses together.

During the user study, users experienced five similar VR scenes and we assigned one specific set of cues to each scene. The five cues were;

(1) None: No visual and audio cues are provided

(2) Haptic-audio: The user hears the sound of their heart beat and feels the Vive controller vibrating

(3) Haptic-visual: The user sees an animation of their heart beating, and feels the Vive controller vibrating

(4) Audio-visual: The user hears the sound of their heart beat and sees an animation of their heart beating

(5) All: The user experiences all of the visual, audio and haptic cues. The presentation of cues and scenes were counterbalanced using a balanced Latin square.

The five scenes assigned with one specific cue were randomized in the user study. The VR scenes were designed to create specific emotional responses. In our user study, there are 5 scenes and each has five different segments designed to create a different emotional response (happiness, anxiety, fear, disgust, and sadness). For example, figure 1 shows 5 pictures of different emotion segments in one of our five VR scenes. The happiness segment has butterflies flying around the user's virtual vehicle and beautiful flowers, green grass and trees were also in the scene. In the anxiety segment lions were attacking another vehicle and the driver was crying for help. The fear segment has a T-Rex roaring towards the user's vehicle and the disgust segment showed rotten animal's bodies and blood littered along the road. Finally, the sad scenario had a wolf cub whose mother had been killed, and was walking around his mother's corpse with a mourning sound.

We collected data from 7 participants (one female) in the user study, with ages ranging from 27 to 58 years (M=37.1). All participants had normal or corrected to normal vision.

4.1. Procedure

After welcoming participants and explaining the study, we asked them to stand in a resting position. The user was then asked to put on the Polar H7 chest strap. The H7 was used to measure the heart rate because it provides very accurate heart rate sensing when doing exercise [WBD*16]. The strap of the sensor was attached to the skin around chest across the heart. The participants would be told that the user study was a jungle safari. Their heart rate was visualized to audio, visual and haptic on the HTC Vive controllers. During the user study they would have five conditions, haptic-audio, haptic-visual, audio-visual, all and none of them. In the user study, they could rotate their head to see different directions of the views but cannot move their body. The visual cue of heart rate in VR scene was fixed on the VR main camera so that the cue followed the rotation.

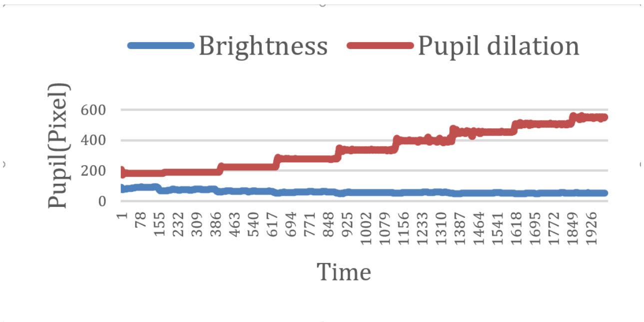

Figure 6: *Baseline.*

After this, the user put on the HTC Vive headset and a baseline VR scene was shown to perform a pupil diameter calibration. This VR scene was only an empty room without anything else. The brightness in the virtual room was then changed from complete darkness to very bright whiteness over 60 seconds in 9 step increments of brightness. The change in brightness was measured by the light sensor in the HMD and the pupil diameter response to the change in brightness in the HMD was captured with the Pupil Labs hardware and software. Each user's response was different, and the relationship between the brightness and the pupil dilation for one person is shown in the Figure 5. As expected, with increasing brightness the pupil diameter decreased. The user's pupil response to brightness variations was used as a baseline to measure additional pupil diameter changes due to their emotion response.

After this, the VR scenes were played for the user and each scene was shown for around 4 minutes. There were 5 scenes in total. In the VR experience the user was standing in a vehicle that automatically moved through the virtual safari. The user could turn their heads, and move their bodies slightly, but the vehicle path was preprogrammed. After each scene, there was a mandatory break of minimum three minutes. While the user was experiencing the VR scene we continuously measured their heart rate and pupil diameter. In the next section we report on the results of this data collection.

5. Results

During the baseline measurement, the user experienced an empty room and the brightness changed from minimum to maximum. At this stage, we assumed that there was no emotion involved in experiencing the VR in users and the pupil size was only affected by the luminance in the headset.

The brightness (Minimum is 0 and maximum is 8) was divided equally into 9 parts at baseline, matching the 9 brightness levels. Each subject has an individual pupil response to the change in brightness. One paired data set (brightness and pupil dilation) of one subject is shown in Figure 6. According to the work in [WY12], to get the trend line of the pupil dilation response to change in brightness a third order polynomial was fitted to the observed data. For each subject we created a pupil dilation response measure according to the baseline data.

We assumed that the brightness and the pupil dilation of each participant was paired in their own curve line and the relationship of brightness and pupil dilation in the baseline is shown in Figure 5. The formula was in the figure as well. For example in Figure 5

$$y = -3E^{(0.6)} * x^3 + 0.0036 * x^2 - 1.5827x + 315.66$$

where x means the luminance and y means the pupil dilation at the value of the specific luminance, x.

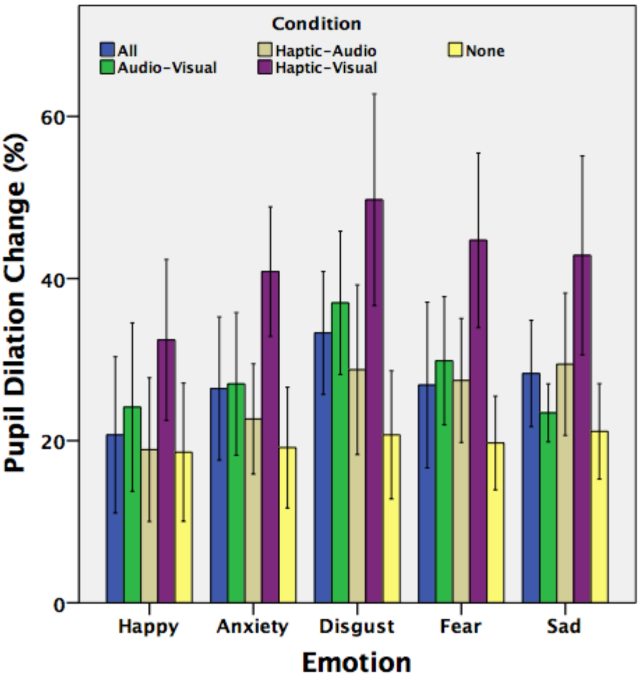

Figure 7: *Pupil Dilation Change (%) in each emotion for all conditions. Whiskers represent ± 95% confidence interval.*

When users experienced the emotional VR environments, the brightness and the pupil dilation were captured and recorded at 30 samples/second by the arduino. The brightness at each point in time was input into the users individual baseline formula, and the baseline pupil dilation response found. This is how much the pupil should be dilated without any extra effect due to emotional response. Assigning $pupil_{total}$ to be the pupil dilation captured in the emotional VR scene, $pupil_{emotion}$ is the pupil dilation affected by VR experience without brightness and $pupil_{brightness}$ the pupil dilation affected by the brightness. So from the equation following,

$$pupil_{emotion} = pupil_{total} - pupil_{brightness}$$

the pupil dilation caused by the VR experience can be found. The $pupil_{emotion}$ was the pupil dilation caused by the emotional arousal in the VR experience.

Using the $pupil_{emotion}$, we measure the change in pupil dilation (in % values) from the baseline and ran a two-way repeated measure ANOVA using the data with emotion and condition being the two levels (Figure 7). We found significant main effect of emotions on pupil dilation change—F(4,24) = 9.05, p<.001, η_p^2 = .6. A pairwise comparison with Bonferroni's adjustment found that *disgust*

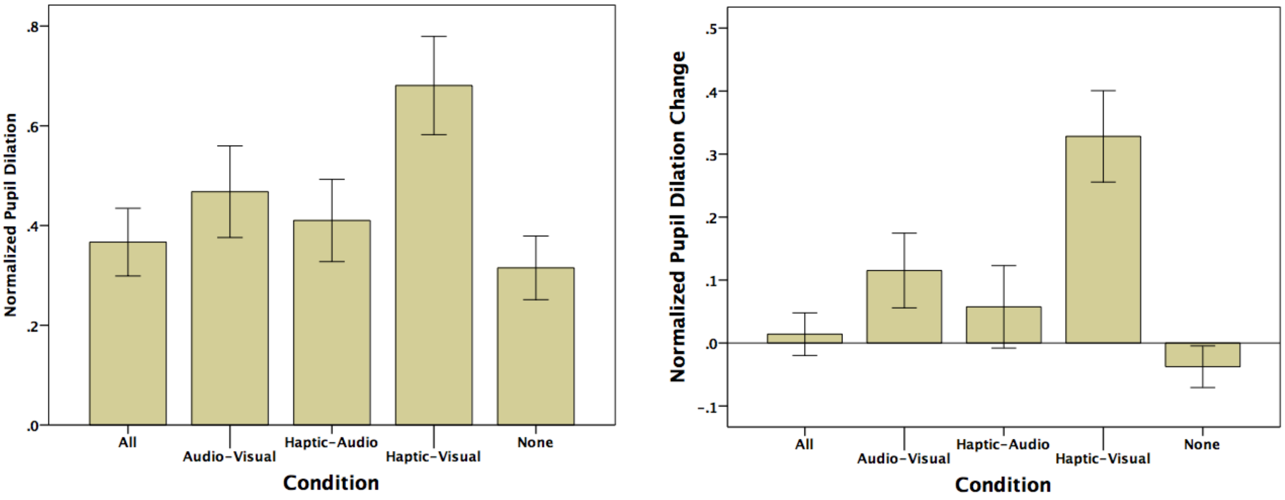

Figure 8: *Normalized Pupil dilation (left) and normalized pupil dilation change from baseline (right). In case of None condition, negative dilation change indicates less dilation than in baseline. Whiskers represent ± 95% confidence interval.*

had significantly highest pupil dilation change than all other emotions. *Happy* had significantly least pupil dilation change than all other emotions except for sad.

We also found a significant main effect of conditions in pupil dilation change—F(4,24) = 25.3, p<.001, η_p^2 = .81. With a pairwise comparison we found that the Haptic-Visual condition had significantly higher pupil dilation change than the Haptic-Audio, Audio-Visual, and None conditions.

There was a significant interaction effect of *Emotion* × *Condition*—F(16,96) = 2.45, p=.004, η_p^2 = .29. We noticed that the pupil dilation did not change much for the None condition across all emotions (Figure 7). However, the Haptic-Visual and Audio-Visual conditions had clear changes in pupil dilation between different emotions. This shows that in the None condition the pupil dilation is about the same, but adding additional cues could cause a greater difference in dilation results.

In our research, there are three types of HR cues were shown to the participants (audio, visual and haptic). Figure 8 shows the average change in percentage of pupil diameter above the baseline measure across all the VR scenes for each of the heart rate conditions. To compare the pupil dilation response between different conditions we used a repeated-measure ANOVA analysis on the $pupil_{total}$. We found an almost significant effect of the condition in the dilation change F (1.22, 6.09) = 4.33, p = .08, η_p^2 = .46 (Figure 9).

However, different environments in the experiment had different brightness, and participants looked in different directions in the immersive scenes, which also varied the brightness across participants even in the same environments. To eliminate the potential confounding effects of brightness on pupil dilation we normalized the data for unit brightness using this formula:
normalized pupil dilation = *pupil dilation / brightness*.

Using a repeated-measure ANOVA, we found that the condition used to present the heart rate data had a significant effect on normalized pupil dilation change (from baseline) F(2.01, 10.04) = 37.76, p <.001, η_p^2 = .88 (Figure 8). The data violated the assumption of sphericity so we applied a Greenhouse-Geisser adjustment. A pairwise comparison with Bonferroni's adjustment revealed that Haptic-Visual condition caused significantly higher pupil dilation change than all other conditions with $p < .01$.

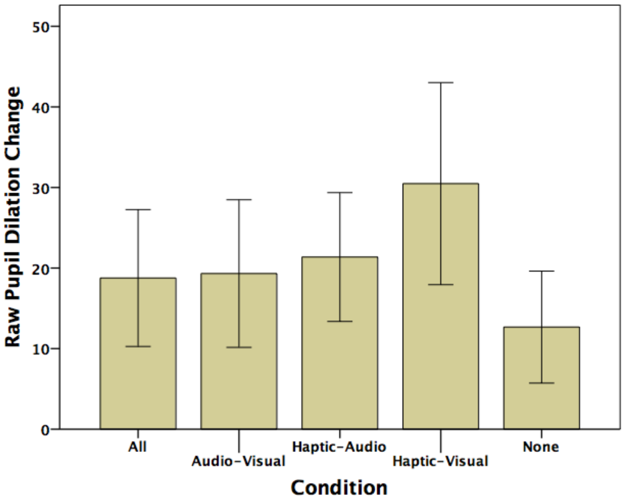

Figure 9: *Raw pupil dilation changes from baseline. Whiskers represent ± 95% confidence interval.*

6. Discussion

The primary purpose of this study was to explore if pupil dilation could be used to monitor the user's emotional arousal states in the VR experience. From previous research, using images and audio cues, we know that the pupil dilation could be increased in response to emotional arousal. We also know that VR scenes could evoke emotions in users.

In this research we designed five VR scenes and each scene had five different emotion segments, including happiness, sadness, fear, disgust, and anxiety. These five emotion segments were designed to evoke specific emotions when the user experienced the VR scenes. From the Figure 7, all the emotional scenarios in the five scenes increased the pupil dilation in the users. From the knowledge of investigating pupil responses to emotional arousal images or audios, both negative and positive arousal images or audios could enlarge pupil dilation [PS03, BG12, BMEL08]. The results are consistent with those in arousal images and audio researches and also proved that the scenes that we designed could evoke negative or positive arousal in users in another way.

In our user study, the condition of haptic-visual cue in the VR scenes produce the biggest increase in pupil dilation in the five conditions, in Figure 7. The visual cue in the VR scene is scaled according to the real-time heart rate. The cue is a heart shape, showed in the "a" picture in Figure 1. When the virtual heart is beating, it is like a red cue flashing in front of users. Especially when the heart rate increases, the cue would be scaled to be faster and bigger. When experiencing the VR scene, the user has to spare attention to the virtual heart shape. In Kahneman et al.'s [KB66] research, high level cognitive workload could enlarge pupil dilation. In our study, maybe the visual cue increased the cognitive workload in user so that the pupil dilation increased the most in the condition with visual cue. Since The visual cue is causing the user to divide their attention between the objects in the VR scene and the beating heart in the HUD interface.

Another explanation to the result that the haptic-visual condition has the biggest pupil dilation increase could be that visualizing physiological cues in the VR scenes is distracting to users, and causes extra emotions except the targeted emotions when they were experiencing the VR environments during our user study. From the post interview, we asked participants questions like "which cue do you like the most?" "which cue do you dislike the most?" "Do you notice the cues?" Users said that audio is the best feedback among these three feedback, and that the visual cue is distracting and negatively affects the experience in the virtual safari. Participant 5 noted that "Yes, the audio and the visual cues are pretty easy to be noticed, but the visual cue distracted my attention". There is potentially a confounding effect of visual cue distracting and annoying participants and consequently evoking additional emotion except the targeted emotions in the VR experience, which may lead to additional change in pupil dilation. However, this effect is subject to further investigation.

At the same time we noticed that None condition did not have any noticeable pupil dilation change in different emotions. It indicates that not having a feedback of heart rate causes less emotional arousal than when having it. It leads to an interesting finding, which needs further validation, that in the presence of heart rate feedback pupil dilation change can be used as an indicator of emotion.

Another interesting finding is that in case of normalized pupil dilation None condition had smaller pupil dilation than baseline condition. It also indicates that not having a physiological feedback, in our case heart rate, may be detrimental to emotional arousal in VR environments.

7. Conclusions and Future Work

In this paper we investigated the pupil variation by using the positive or negative affective VR scenes. From the results, the pupil diameters in both positive and negative emotional segments increased. We noticed that haptic-visual feedback increased the pupil diameter the highest in all conditions, while not having any feedback cues produced the least pupil dilation. It is clear from our results that pupil dilation is effected by VR environments and more studies are needed to establish the relationship between pupil dilation and emotional arousal in VR.

Currently some interesting research being carried out by the machine learning community to measure emotion from physiological signals such as heart rate and GSR. Compared to physiological signals, the pupil dilation is varied much faster [PS03] and could reflect emotional arousal. In the future, pupil dilation could also be used to measure emotion similar to physiological signals.

In recent research, subjective surveys are the most popular methods for measuring emotional arousal. Recently, the physiological signals such as heart rate and GSR are attracting significant attention in measuring emotions, however, the objective measurements are limited. With more research, pupil dilation could be adopted as an objective measurement of emotion, particularly in the human-computer interaction domain.

From our results it can be confirmed that pupil dilation reflects arousal in VR. But we do not know the extent to which pupils are dilated in response to specific arousal. The relationship between the luminance and pupil dilation has been explored by many researchers, such as Watson al et. [WY12], Winn al et. [WWEP94] and [Bar99]. Whether the relationship between arousal and pupil size could be formulated in a similar way as the the relationship between the brightness and the pupil dilation is an interesting topic for future research.

There are a number of areas of improvement for future research. During our study, every participant had to take off the Vive headset after finishing each scene. After that, they put the headset on again. As the headset moved and its position changed on the head, the pupil distance to the camera might have been changed as well, which we did not to take into account in our study. In the future, we would just use one reasonably longer scene to measure the pupil dilation. In this experiment, we designed the VR environments ourselves. The graphics quality was not as good as the commercially available VR games. In the future, we will validate our findings using commercial games. This work is one of the initial explorations of pupil dilation in VR environments. We expect to build more research on top of this and hope our results will inspire other VR researchers to consider investigating this interesting topic.

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