SERENITY IN THE HEAT OF BATTLE

An EEG-based brain-computer interface to promote relaxation via a virtual reality game

Author: Gordon Lucas, *Amsterdam University College*

Email: gordon.lucas@student.auc.nl

Supervisor: Michael McAssey, *Amsterdam University College*

Email: m.p.mcassey@auc.nl

Reader: Rob Belleman, *Universiteit van Amsterdam*

Email: R.G.Belleman@uva.nl

Tutor: Melanie Eijberts

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Abstract

Research on brain-computer interfaces (BCIs) has grown rapidly in previous years. Newly developed low-cost EEG headsets allow for non-invasive recording of neural activity and could bring BCI applications to a wider public audience. Promising applications include meditation, stroke recovery, patients of locked-in syndrome, treatment and mental illnesses, such as attention-deficit hyperactivity disorder (ADHD), as well as video games. The commercial release of new virtual reality (VR) devices had led to increasing interest in combining BCIs with VR to create uniquely immersive environments. This work investigates further possibilities of this technological fusion to promote relaxation with the creation of an EEG-based BCI, which changes the difficulty of the commercial video game *Superhot VR* based on the player's state of relaxation. The effectiveness of this system was tested in a within-participant design. 15 participants played the original and BCI version of *Superhot VR* for 5 minutes each and reported their experiences on the GEQ. Results of the experiment suggest a slight increase in relaxation during the BCI version and no loss in perceived control and enjoyment. Further implications for research and the therapeutic potential of these findings are discussed.

Keywords: Brain-computer interface (BCI), Virtual Reality (VR), Electroencephalography (EEG), video game, Oculus Rift, relaxation, meditation

Introduction

Brain-computer interfaces (BCIs) have become a flourishing field of research in the last two decades. The underlying idea is to enable users to interact with computer applications directly via measures of brain activity. Most BCIs use electroencephalography (EEG) as a means of non-invasively measuring brain activity. EEG is particularly suited for BCIs because of its high temporal resolution. In addition, EEG headsets are portable and cost comparatively little. Brain-computer interfaces may also relay neurofeedback to their user. This feedback can be used to help a user improve their performance, for example during meditation.

There currently exist four EEG-based BCI paradigms (Marshall, Coyle, Wilson, & Callaghan, 2013): In so called 'passive' BCIs, a user's mental activity is translated into a measure of mental performance, such as relaxation or agitation, by measuring amplitude changes in alpha band (8-12 Hz) waves. The BCI then uses these metrics to inflict changes in the desired application. In this paradigm, the EEG may be replaced or complimented by other physiological measures, such as electrocardiography (ECG) or galvanic skin response (GSR). The second paradigm makes use of steady-state visually evoked potentials (SSVEP). These potentials are elicited when a user is focusing on a visual stimulus that flickers in a specific frequency. Different frequencies elicit unique SSVEPs. Using stimuli flickering at distinct frequencies, the BCI can detect which stimulus a user is directing his gaze toward. This paradigm therefore allows for selection amongst multiple items or choices. Similarly, a BCI can infer a user's choice via the P300 paradigm. The P300 event-related potential is a distinct peak in electrical activity, which occurs 300ms after the sight of a target stimulus. The last BCI paradigm allows users to interact with a computer system using mental imagery. Imagining different movements result in distinct activations in the EEG, which can be measured by the BCI to generate mental commands. The commands must previously be learned by the software in a lengthy training session before they can be employed reliably. Because of this, it is not possible to easily switch between users in this paradigm. However, the mental commands can be translated into mouse clicks or key strokes, offering great flexibility for user input. Combinations of these paradigms are possible, yet few studies have so far attempted this.

EEG based brain-computer interfaces have several advantages: They are non-invasive, cheap, portable, often wireless and they measure brain activity with high temporal resolution. These advantages are particularly relevant for application in video games. However, EEG is also sensitive to noise, such as muscle or eye moments, reducing its reliability when used as a form of input for games. Furthermore, a BCI based on mental commands requires a lengthy training session. Brain activity differs between individuals, so the BCI must be trained for each individual separately. Mühl et al. (2009) mention that 20% of the population is “BCI illiterate”, meaning their EEG readings are not convertible into reliable controls for a video game. Despite these difficulties several BCI video games have been developed. Various noteworthy examples will be discussed in this thesis.

Brain-computer interfaces find application in many fields. Firstly, they may enable new ways of communication for disabled individuals. For instance, patients with locked-in syndrome, who cannot use mice or keyboards, can instead make use of brain-computer interfaces to communicate. Secondly, BCIs are used in rehabilitation settings, for example to aid in the recovery after a stroke (Spicer, Anglin, Krum, & Liew, 2017). Furthermore, they appear to be a promising novel treatment for certain mental disorders, such as ADHD in children (Blandon, Munoz, Lopez, & Gallo, 2016; Lim et al., 2012; Munoz, Lopez, Lopez, & Lopez, 2015). Another useful application currently under investigation, is to support meditation with the neurofeedback provided by BCIs (Kosunen et al., 2016). Besides their clinical use, BCIs are also often designed for healthy subjects. Video games are a common application, as BCIs provide novel and exciting methods of input to enrich the gameplay experience (Mühl et al., 2009). Not only have they been applied to commercial video games, for example *World of Warcraft* (Van de Laar, Gürkök, Bos, Poel, & Nijholt, 2013), but researchers have also developed entirely new games, such as *Bacteria Hunt* (Mühl et al., 2009) or *BrainBasher* (Bos & Reuderink, 2008).

The recent release of the Oculus Rift and HTC Vive was followed by creation of increasingly sophisticated virtual reality (VR) games and environments. So far, however, few studies have examined the application of BCIs in VR games. It is therefore still unknown if such a combination of devices is feasible. Most VR games require the player to move around in a small play area, but EEG recordings might be affected by such movements. This obstacle could prove to hinder a full integration of BCIs into VR games and needs to be researched. Furthermore, although roughly 35% of studies make us of a passive BCI design (Ahn, Lee, Choi, & Jun, 2014), no games have been developed that use passive BCI to change the difficulty of a game (Marshall et al., 2013). This could however improv the experience of the game dramatically. Tuning a game's difficulty based on emotion, for example, might help to avoid frustration while playing. Or a BCI measuring attention could help to bring the player into a flow state, a state of heightened concentration in which her skills are matched with her current challenge. It is thus relevant to explore this possibility.

To fill this gap in research, the author developed an EEG-based passive BCI for the commercial game *Superhot VR* (Superhot Team, 2016). *Superhot VR* is a minimalist shooter, in which time only passes when the player moves. The BCI changes this rule based on the user's state of relaxation, which was recorded via EEG. The more relaxed a user, the slower time passes, decreasing the difficulty of the game. *Superhot VR* was chosen because its unique time mechanic makes it possible for players to stand still for a brief moment of rest. This mechanic was designed with the explicit aim to increase relaxation, because this technique may then contribute to the creation of better meditation environments. An experiment was implemented to determine whether the added game mechanic successfully motivates the user to relax. However, it is possible that the new mechanic interferes with the enjoyment of the game. How well are players able to control their relaxation? Will they get annoyed by the changes in difficulty? The study thus tested whether the added challenge provided by the BCI hinders the user's perceived degree of control and enjoyment of the game. Control and annoyance were assessed via competence and tension scales on the Game Experience Questionnaire

(GEQ) (Poels, de Kort, & Ijsselsteijn, 2007). The experiment thus investigates the following two hypotheses:

***H1**: Relaxation levels will be higher while playing the BCI version rather than the original version.*

***H2**: GEQ scores of competence and tension will not significantly differ between the BCI version and the original version.*

Research Context

In their review of scientific studies on BCI video games Marshall et al. (2013) discuss the applicability of the different BCI paradigms to various game genres. They found more than 50 published studies of BCI games. Most of the reviewed games used BCIs to add another control element to the game. Passive BCIs afford an implementation of passive control, for example changing the objectives or rules of a game. Their advice for games with passive BCIs is that users' neurophysiological response changes in repeated segments of a game. Marshall et al. also suggest implementing more BCIs in existing games to easily increase the variety of games offered. The present study followed this advice by implementing a passive BCI that changes difficulty in the commercial video game *Superhot VR*. In 2014, Ahn, Lee, Choi & Jun surveyed researchers', developers' and users' opinions on BCI applications. Their literature search revealed a substantial increase in publications on BCI games after the Emotiv EPOC and other wireless EEG devices were released. These devices are considerably cheaper than previously available devices. This review also shows that 94% of BCI games used EEG paradigms, with the Emotiv EPOC used in 43% of these cases. A majority (77%) of the 294 participants rated the potential influence of future BCI games as 'high' or 'very high'. Even greater expectations were found for the application of BCIs in rehabilitation or prosthesis. Developers and researchers of BCI games stressed the importance of short training times and easiness of use. Keeping these factors in mind, the present work attempts to minimize training time and maximize the easiness of use, to facilitate the best possible user experience.

The Game Experience Research Lab in Eindhoven developed the Game Experience Questionnaire (GEQ) (Ijsselsteijn, Kort, & Bellotti, 2007) to quantify user experience in games. The GEQ assesses immersion, tension, competence, flow, negative affect, positive affect and challenge. The consistency of the subscales of the GEQ as well as their reliability have been validated. Still, the researchers recommend combining data gained via self-report with psychophysiological and behavioral measures. The GEQ was used in various studies with BCI games to evaluate participants' experiences (Bos & Reuderink, 2008; Van de Laar et al., 2013; Mühl et al., 2009). Currently, no standardized questionnaire for BCI applications exists (Van de Laar, Gürkök, & Bos, 2011).Van de Laar, Gürkök and Bos (2011) discuss the applicability of the GEQ and other, more specific questionnaires in research with BCIs. Although the GEQ might require small adaptations, as it assumes input from keyboard or controllers, it is suggested to be a robust option for an evaluation of user experience in BCI games. While the applicability of the GEQ for virtual reality games has yet to be examined, the advantages highlighted above are assumed to qualify the GEQ for the current research. Van de Laar et al. (2011) also discuss the inclusion of neurophysiological signals in the evaluation of user experience to achieve more objective results. Most BCIs already include an EEG, which opens the possibility of measuring emotions. Emotions play a role in the user experience especially for usability and playability. Furthermore, measures of galvanic skin response (GSR) and heart rate, via electrocardiography (EKG) could contribute to the evaluation of emotions. Importantly, these measuring devices must not influence the user experience. Concurrently, other researchers evaluated the use of GSR and EKG for an objective evaluation of user experience with VR specifically (Egan et al., 2016). Their subjects played either a VR or non-VR version of a game and reported their experience of immersion and usability in a short questionnaire. Their pilot study showed a significant correlation ($r = .407$) between GSR and the question "I needed to learn a lot of things before I could get going with this system", indicating that a lower physiological response is associated with less difficulty learning to control the gaming system. Easiness of use and short training duration have been identified by Ahn et al. (2014) as important determinants of the success of BCI games. Measurements of GSR could therefore provide a quantitative estimation of these factors and thus enrich research on BCI games. However, the relationship between GSR and heart rate and user experience in BCI VR applications is not fully understood. The present work will therefore evaluate the user experience with the help of the GEQ.

Several studies have already employed the GEQ to probe user experience in BCI games (Bos & Reuderink, 2008; Mühl et al., 2009; Van De Laar et al., 2013). *BrainBasher* is a simple BCI game which uses an EEG to record imagined movements (Bos & Reuderink, 2008). The researchers used the BioSemi EEG, but do not indicate reasons for their choice. The BCI version of the game was compared to a keyboard-controlled version. The researchers recruited 15 participants to evaluate their experiences on the GEQ. The participants reported feeling more competent and less annoyed in the keyboard version. The BCI version was significantly more fun, immersive, challenging and provided a richer experience. The researchers unfortunately do not report the accuracy of the BCI system. The keyboard-controlled version was arguably too easy, which might explain these results. Still, the study shows how a BCI can enrich the experience of a video game. A more exciting example of BCI control in a game is *Bacteria Hunt* (Mühl et al., 2009); the researchers combined a SSVEP approach with a passive BCI design based on relative alpha power. This combination of modalities proved to be problematic, as alpha power was significantly higher during SSVEP stimulation. The researchers compared two versions: The game yielded either more (positiveFeedback = pF) or fewer (negativeFeedback = nF) points depending on the relative alpha power. The pF version was hypothesized to result in higher alpha power and as such a greater state of relaxation. However, no support for this was found, possibly because the sample consisted merely of 5 participants. Similarly, no significant differences in the GEQ scores for the two conditions were found. Yet, the authors report a high degree of relaxation in both conditions and thus suggest raising the overall difficulty in future studies to avoid this floor effect. Relative alpha power was also used in a BCI version of *World of Warcraft (WoW)* by Van de Laar et al. (2013). In *alphaWoW* the player's character shapeshifts – granting a second set of abilities -

depending on her state of relaxation. When the player is relaxed the Elf-form grants her the ability to cast spells and heal herself; once she becomes stressed, she transforms into a bear granting her strong armor and close combat attacks. An in-game bar provided feedback about the current alpha power. For this study the Emotiv EPOC was used, since it offers high usability and more sensors for its relatively low price. In this study 42 participants played *WoW* and *alphaWoW* for up to 30 minutes each. After both play sessions a questionnaire was administered to measure presence, fun and control, with added questions to inquire about the shapeshifting control. As expected, the BCI version was rated lower on the scales of control and shapeshifting control. Still, there were no significant differences on the fun scale, indicating that lower control did not weaken the experience. The researchers also found that some participants quickly learned to control their alpha levels. This raises the question whether a game like *alphaWoW* could successfully promote relaxation. So far, no BCI video game has been created for this purpose. There have been, however, attempts at creating BCI-assisted meditation environments (Amores, Benavides, & Maes, 2016; Kosunen et al., 2016; Shaw, Gromala, & Song, 2010). These VR environments successfully teach meditation skills by providing useful neurofeedback and ‘telepathic’ abilities to the user. Whereas *The Meditation Chamber* (Shaw et al., 2010) utilizes GSR, *PsychicVR* (Amores et al., 2016) and *RelaWorld* (Kosunen et al., 2016) both make use of an EEG in combination with the Oculus Rift.

Psychic VR, developed at the MIT Media Lab, combined the MUSE EEG headband with an Oculus Rift to create a playful meditation environment (Amores et al., 2016). The BCI in this study calculated a user’s focus and displayed it in VR. Increasing one’s focus then granted abilities in the virtual reality, such as the power to levitate objects. The research showed that the BCI helped to promote mindfulness and concentration in its users. Similarly, the immersive VR system *RelaWorld*, developed by Kosunen et al. (2016), successfully elicits deeper states of meditation by implementing an EEG-based BCI into a VR environment. The scene developed for this environment placed the user on a platform on a small tropical island surrounded by reference objects, such as trees and other islands. The researchers used an EEG to record alpha and theta waves, which were translated into measures of relaxation and focus. This information was used to create visual neurofeedback in the virtual reality. Greater concentration was visualized by the player and their platform floating upwards, whereas relaxation was portrayed as an energy bubble gaining opacity with increasing levels of relaxation. The application provided two forms of guided meditation: body scan and focused attention. Either practice is supported by a user interface highlighting the current focus point of the meditation. In a 2 (meditation) x 2 (neurofeedback) x 2 (medium) within participant experimental design, the researchers compared the different techniques to determine which is more effectively supported by VR. Additionally, they tested the effectiveness of including or omitting the described neurofeedback mechanism. Lastly, the display medium differed between the Oculus Rift or a regular computer screen. After each meditation session, the participants evaluated their sense of presence and depth of meditation on questionnaires. The results of this experiment showed that VR both increases feelings of presence and elicits higher meditative states. Furthermore, the inclusion of neurofeedback appeared to enhance the experience, yet this finding was not statistically significant. This study thus shows how VR can effectively enrich meditation experiences and promote relaxation, especially in combination with neurofeedback. While the present study did not attempt to create a new meditation environment, it still aims to implement the findings of this previous research. Rather, the system developed for this thesis aimed to playfully create relaxation, by including relaxation directly into a game's mechanics. In this sense it provides a novel approach to using VR to incite relaxation.

Method

Participants

The author recruited 15 students of Amsterdam University College to participate in the experiment. These participants were aged 18 to 23 (mean: 20.4) and 14 identified as male. Nine of the participants had no previous experience with virtual reality. None of the participants reported being susceptible to motion sickness or epilepsy.

Materials

The study adopted the commercially available video game *Superhot VR*, developed by Superhot Team (2016). For the purpose of the study, the developers provided the author with a hacked version, which included an extra library (*Shtclib*) for the manipulation of time in the game. In *Superhot VR* the player is continuously attacked by a series of enemies, which she must eliminate with punches or guns (Figure 1). One may also make use of the surrounding objects, such as ninja stars, cups and frying pans. Crucially, time only passes when the player moves, thus, giving the player time to plan her next moves and dodge incoming bullets. The game was played on the Oculus Rift[1],

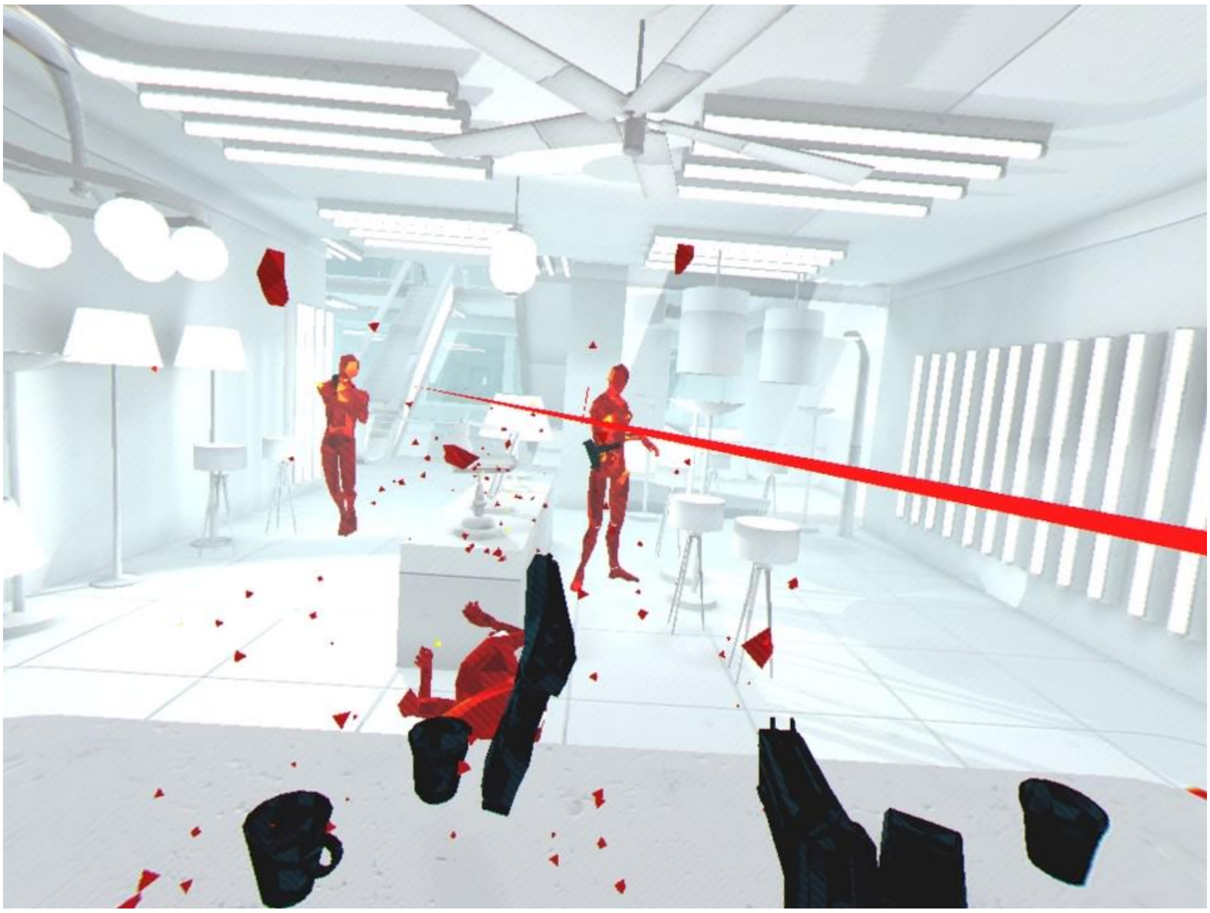

Figure 1: Screenshot from Superhot VR. Enemies are face-less red humanoids, that shatter when hit. Black objects can be picked up and thrown by the player. Incoming bullets leave a red trail, so players can spot them easily.

[1] https://www.oculus.com/

a head-mounted virtual reality display (HMD). Inputs were given via two Oculus Rift Touch controllers. These devices are handled rather intuitively as they simulate virtual hands, enabling the user to form fists and pick up objects.

To measure the participants' brain activity, the wireless Emotiv EPOC[2] portable EEG headset was used. The Emotiv EPOC records electrical activity on the scalp using 14 sensors and 2 references. It connects to the computer running the game via Bluetooth, thus does not hinder the participant from moving around while using the Oculus Rift. Figure 1 showcases how the Oculus Rift and Emotiv EPOC were fitted together on the head. The Emotiv Xavier Control Suit transforms EEG data and displays neurofeedback on a subject's state of attention, focus and relaxation. According to Emotiv's description of their "Five Basic Measures of Mental Performance Metrics" (n.d.), relaxation calculated by the Control Suite measures one's ability to rest. It ranges from 0 to 1, with 1 indicating extremely elevated levels of relaxation. High scores on this measure are typically only obtained by experienced meditators. The author developed an application (EEG-Reader.exe) that collects this information and uses it to change the speed at which time passes in a BCI version of *Superhot VR* (Figure 3). A relaxation baseline was recorded for 30 seconds before starting the game. In the BCI version of the game, time was manipulated to pass more slowly when the user is relaxed – indicated by a score greater than baseline. This makes it easier for the user to avoid enemies and incoming bullets, therefore encouraging the player to stop moving for a moment and rest. Lower levels of relaxation will result in time passing more rapidly. This makes the game

Figure 2: Demonstration of the experimental set-up showing the Oculus Rift VR glasses and Emotiv EPOC EEG headset.

[2] https://www.emotiv.com/epoc/

immensely challenging at lower levels of relaxation. For a detailed explanation of this mechanic see Figure 4.

This app was created in Visual C# with the help of the Emotiv Software Development Kit. Several issues occurred in the development of the BCI: Initially the game time was completely frozen if it was fed values below 0. This error was overcome by switching from raw alpha wave values to the relaxation metric calculated by Emotiv. Later this error returned, whenever the game attempted to read a value at the same time as the EEG reader wrote them into the data set. To avoid this problem a separate file was created in which only the current relaxation value was stored. Lastly, the calculation of the time scale initially scaled purely based of the relaxation score. This led to the game speed fluctuating rapidly and did not work well for separate users. Therefore, the time scale was redesigned to be based on the change of relaxation from a previously recorded baseline.

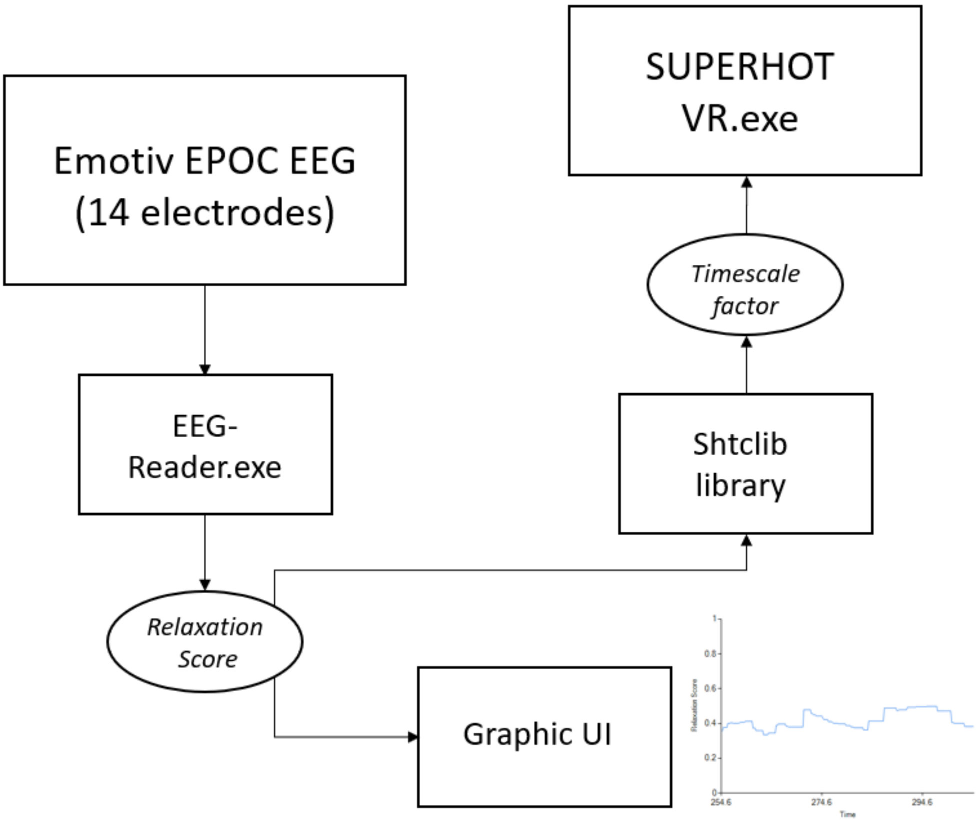

Figure 3: Visualization of the system developed for the experimental protocol. EEG-Reader.exe reads the current relaxation score from the Emotiv Xavier control suite. The relaxation is then fed into the Shtclib and converted into a time scaling variable, which is then called upon by the game.

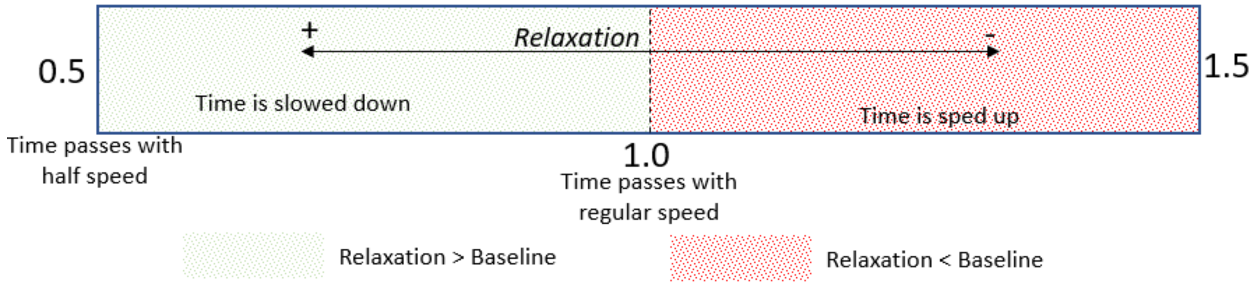

Figure 4: Explanation of the time scaling variable in the BCI version of Superhot VR. While relaxation equals baseline, time passes at the normal speed of the game. Any relaxation levels greater than baseline will increasingly slow down the rate at which time passes. Similarly, relaxation levels below baseline speed up time. The formula used to calculate the time scale is: 1.0 + 2*(Baseline – Relaxation)

Design

The experiment had a within-subjects design. As such all participants played both the original version and the BCI version of *Superhot VR*. To keep potential order effects consistent, all participants played the original (condition 1) first, followed by the BCI version (condition 2). Dependent variables were competence and tension scores on the GEQ and relaxation. Relaxation was defined as the variable calculated by Emotiv Xavier Control Panel. In each condition, the average relaxation per minute was calculated for each participant, resulting in 5 repeated measures per condition. As an additional measure of relaxation, the item "I felt relaxed" was added to the GEQ. The GEQ metric of competence is probed with questions such as "I felt skillful" and "I was good at it". Tension was assessed with "I felt annoyed" and "I felt frustrated" amongst others.

Procedure

All subjects were invited to the laboratory, located at the University of Amsterdam science faculty. After giving their consent, they were asked to report their previous experiences with virtual reality and fill in some information about their age and gender. Then the Oculus Rift and Emotiv EPOC were fit on the head and adjusted until all electrodes showed optimal contact quality (Figure 5). Participants without VR experience were given a brief introduction to the setting and the controls. Each participant was given enough time to learn the game before the recording started by playing through the first 5 levels in *Superhot VR*. On average this took the participants around 15 minutes. In condition 1, the participants played the original version of *Superhot VR* for 5 minutes. Once finished with playing, the participants took a short break, in which they reported their experiences on the GEQ. After this break, the same procedure was repeated with Condition 2, in which the BCI version was played.

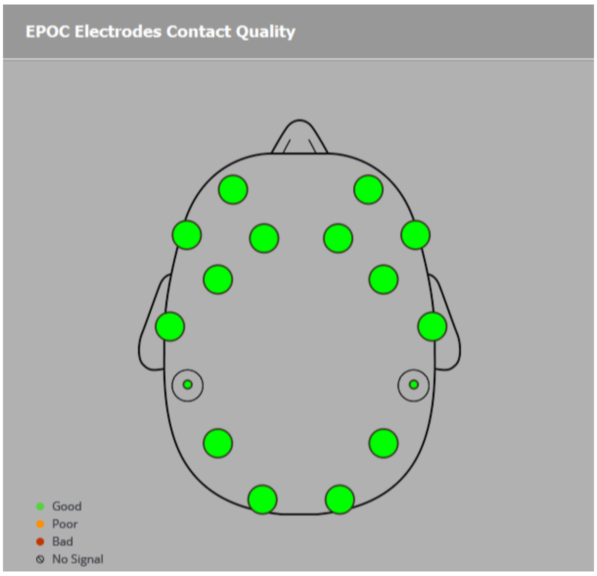

Figure 5: Picture of the interface in the Emotiv Xavier Control Suite, which provides assistance to set up the electrodes correctly.

Participants were advised to take moments of rest, should they feel the game becoming too difficult. Before leaving the laboratory, the participants received a debriefing on the purpose of the research and were thanked for their contribution. In total the experiment lasted for about 60–75 minutes.

Results

For two participants data was missing because of the EEG malfunctioning, so they were excluded from the analysis. Data collected from the EEG was averaged for each minute and then analyzed via a general linear model with repeated measures. This analysis found a significant effect of condition on relaxation (Wilks' Lambda .651, p = .026). Looking into the direction of this effect, it was found that relaxation was higher in Condition 2 (BCI version). The marginal means of relaxation per condition are plotted in Figure 6. This graph shows that relaxation starts at the same level, but then gradually decreases during the non-BCI version of *Superhot VR*. For the BCI version on the other hand, it initially decreases, but then reaches a peak during minute 4, after which it levels out again. Analysis of the EEG data also revealed no significant effect of time itself (Wilks' Lambda .745, p = .571). Additionally, no significant interaction between time and condition was found (Wilks' Lambda .393, p = .056).

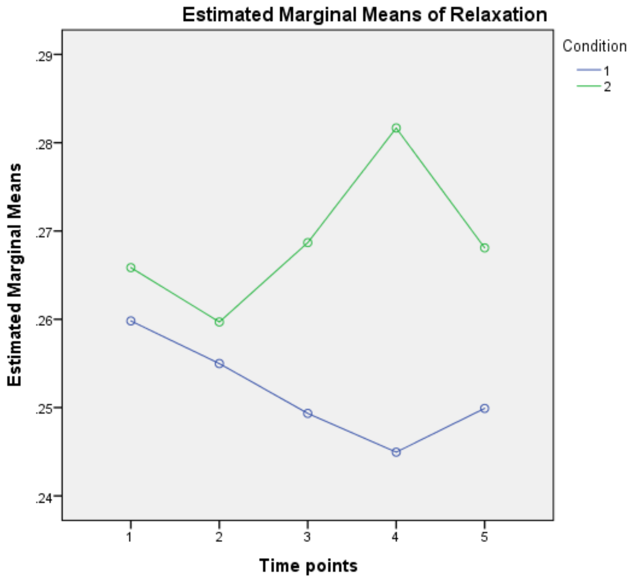

Figure 6: Plot of relaxation scores over time by condition. The green line plots relaxation during the BCI version of Superhot VR, whereas the blue line represents relaxation during the unchanged version of Superhot VR.

Paired sample t-tests were conducted to compare the answers on the GEQ for the two conditions. The results of this analysis are summarized in Table 1. None of the seven measures differed significantly between the conditions. For the added question "I felt relaxed" a significant difference was found (p=.017). The respective means for this item reveal higher scores on average in Condition 2.

Table 1: Summary of scores on the Game Experience Questionnaire (GEQ). Cond 1 = original version of Superhot VR, Cond 2 = BCI version of Superhot VR, M = mean, std = standard deviation. * denotes significance (α =.05)

		Cond 1		**Cond 2**	
	p-Value	M	std	M	std
Positive Affect	.164	4.344	.439	4.167	.743
Negative Affect	.432	1.689	.449	1.767	.511
Competence	.774	3.600	.678	3.544	.670
Immersion	.741	4.056	.510	4.011	.768
Flow	.411	4.356	.594	4.433	.594
Tension	.132	2.444	.766	2.133	.790
Challenge	.668	3.622	.494	3.567	.530
Relaxation	.017*	2.667	.899	3.467	.743

Discussion

The results obtained in the experiment provide evidence to support both research hypotheses. The main goal of the experiment was to determine whether a BCI could promote relaxation in a virtual reality video game. It was thus hypothesized that players' relaxation levels would be higher in the BCI version of *Superhot VR*. Measures of relaxation obtained from the EEG revealed that relaxation during the BCI version were slightly higher than during the original. This seems to suggest that including this measurement of relaxation into the game's mechanics actively promoted the players to relax. This effect appears to be a small effect, however, as relaxation scores in the two conditions differed only by a small margin. Interpreting the actual size of this effect would require an exact definition of how Emotiv Control Suite calculates this metric. Yet, after several inquiries at the headset's developer, Emotiv informed the author that this information will not be made public. Therefore, the validity of this measurement may be dubious. Secondly, the evidence at hand suggests that this relaxation is not lasting. While the BCI version incited on average higher relaxation compared to the original version, scores quickly sank back to baseline (see Figure 6). This might very well be explained by the nature of *Superhot VR*'s gameplay: The player is constantly in danger and has to fight of enemies. The game itself is just not calm or relaxing. It is thus not surprising to see that in condition 1, relaxation steadily decreased. In condition 2 then, players initially became less relaxed by playing the game, which increased the speed —and therefore the difficulty—of the game. To compensate for this, players would then stand still for a moment to take a few deep breaths. Seeing how these relaxing breaks were the intention behind the design of the BCI, this was a considerable success. I suggest that in further research a similar game mechanic is implemented into a more peaceful game, to determine whether this could help players towards a longer lasting rise in relaxation.

Crucially however, the observed data might be explained by an alternative explanation: Noise in the EEG signal might have contributed to the accuracy of the findings. The performance metrics calculated by Emotiv Xavier are sensitive to noise from head movements and badly placed sensors. Even under ideal conditions (see Figure 7) brief instances of noise occurred, causing relaxation to level back to baseline. As mentioned previously, no information could be obtained regarding the calculation of these scores, which makes it challenging to interpret what exactly caused the noise.

Figure 7: Screenshot of Emotiv Xavier Controlpanel demonstrating how the EEG was unable to calculate performance metrics due to noise. Even under perfect conditions (see top right) there were moments in which the signal was too noisy for an accurate calculation of relaxation.

From observing the behaviour of the software during the experiments, it was concluded that the noise was mostly due to rapid head movements. The observed findings might then stem from the fact that in the BCI version players would occasionally stand still to relax. In these pause moments the noise subsided, leading to rising relaxation scores. Since these head movements are an unavoidable part of using the Oculus Rift, this is a difficult problem to solve. Perhaps the adoption of improved EEG headsets, such as the Emotiv Insight[3] or the Muse headband[4] could have prevented this issue. These devices are considerably smaller and thus fit easier on the head in conjunction to the Oculus. Interestingly, the Muse headband is designed specifically for

[3] https://www.emotiv.com/insight/
[4] http://www.choosemuse.com/

meditation and relaxation and would have been ideal for the presented BCI. Currently however, this problem significantly weakens this study's findings.

To overcome problems with the EEG, an additional measure of relaxation was obtained via the Game Experience Questionnaire (GEQ). The added item "I felt relaxed" was rated significantly higher for the BCI version than the original *Superhot VR*. This adds further evidence suggesting that the new game mechanic helps players to find relaxation while playing the game. Evidence obtained via the GEQ is purely subjective, however. Additionally, participants were informed about the BCI game mechanic. From this, they may have deduced the purpose of the study and their answers on this item might have been biased towards greater relaxation in Condition 2. This support for the first hypothesis is thus rather weak and should be interpreted with caution. To generate an even more accurate assessment of relaxation the inclusion of an EKG might be beneficial for future studies.

The second research hypothesis tested whether the BCI would interfere with the enjoyment of the game. If the added game mechanic reduces the control that players experience or create an unsurmountable challenge, lower scores of competence on the GEQ were expected, as well as higher scores of tension. No such differences were found. Consequently, there is reason to believe that the added game mechanic does not harm the experience of the game. One participant even commented that he preferred the BCI version of the game, because he felt that the faster speed of enemies was a more appropriate challenge. User experience is a very subjective quality, which is why the GEQ was chosen in this research. Of course, the implementation of any BCI game mechanic requires delicate fine-tuning if it hopes to enhance the experience of a given game. Luckily, the game mechanic developed for this experiment proved to operate smoothly in the given environment. The changing of game time based on the relative level of relaxation compared to a baseline, especially, made it possible for the BCI to react appropriately to every individual. Furthermore, the effects of pausing for a moment to relax were visible in the game world almost instantly. For example, bullets flew noticeably slower, empowering the player to use this mechanic to their advantage.

An important weakness of the BCI developed for this study was the absence of any visual or auditory feedback in the game. The inclusion of neurofeedback in virtual reality has been shown in previous studies to elicit higher levels of relaxation (Kosunen et al., 2016). As such, it could have strengthened the observed effect in this research, if the participants were able to see their current state of relaxation. In the BCI version of *World of Warcraft* by Van de Laar et al. (2013) the researchers created a small bar for the game's user interface that showed players their current alpha levels. A similar implementation could have perhaps been used for this study. Alternatively, feedback on the current speed of time could have served the same purpose. One possibility would have been to add background music to *Superhot VR*, which speeds up or slows down alongside the game speed. Any such addition to the game would have required further changes by the game developers to the provided hack of *Superhot VR*.

Nevertheless, the findings of this study suggest that the implantation of mechanics based on passive BCIs are feasible. Additionally, it is shown that a game mechanic based on relaxation motivates players to take short breaks and relax. The results of the present study are transferrable to real-life contexts, in the sense that *Superhot VR*, the Oculus Rift and the Emotiv EPOC are all commercially available products. Both devices are easy to use and relatively low-cost, which suits an easier transition into a therapeutic or recreational context. The highlighted challenges of combining the Emotiv EPOC EEG with the Oculus Rift demonstrate the need for further development of compatible devices. To overcome these issues developers of VR devices and EEGs must work together. Such initiatives are slowly starting up. For instance, the Neurosky Mindwave[5] EEG headband hopes to deliver a smooth integration of BCIs into VR games. The fusion of these technologies will perhaps replace controllers as the default input device for VR video games.

[5] https://store.neurosky.com/pages/mindwave

The present research contributes to this evolution by addressing important questions for the future development of virtual reality and brain computer interfaces: The experiment showed that combining virtual reality, specifically the Oculus Rift, with a brain-computer interface is feasible and gives rise to interesting gameplay. This knowledge can be used by game designers and researchers to start thinking about developing further ideas for BCI applications in games. These new games will not only serve entertainment purposes, but likely also contribute to research and therapy. On the one hand, VR graphics are becoming progressively realistic. Combining these graphics with EEG based BCIs will allow researchers to conduct sophisticated experiments and measure brain activity in a plethora of interesting situations. On the other hand, meditation is already showing itself to be a fruitful application of VR and BCIs (Amores et al., 2016; Kosunen et al., 2017; Shaw et al., 2010). Research on meditation is far from conclusive, but its usefulness in the treatment of various disorders continues to be uncovered (Kosunen et al., 2016). Virtual reality and neurofeedback provide effective assistance for meditation and can help novices in learning the techniques. In the future we might therefore see a rise of VR BCI applications in many therapies. Such interventions are currently being investigated, for example in the treatment of attention-deficit hyperactivity disorder (ADHD). BCI video games, such as *The Harvest Challenge* created by Columbian researchers (Munoz et al., 2015) aim to promote relaxation and focus in children with ADHD, and therefore teach them to overcome their disorder.

Conclusion

Interest in the combination of virtual reality and brain-computer interfaces continues to rise. This innovation promises an entirely new level of immersion. This is particularly exciting for the video game industry, because implementing BCIs into video game design enables new strategies for user input and control in the game. BCIs could also contribute by passively altering the game world based on measured brain states. In this work, the speed of time in *Superhot VR* was altered according to the user's state of relaxation. The added game mechanic challenged the player to take breaks from fighting to relax, in order to keep the game's difficulty at a manageable level. Evidence collected in an experiment suggests that the passive BCI did not reduce the controllability of the game. In the future, game mechanics, such as the one presented in this experiment, might therefore become more popular. Currently however, there still exist problems in combining EEG-based BCIs with VR devices, like the Oculus Rift. In the presented study players moved their bodies, which led to noise in the EEG signal. Such problems will perhaps be minimized with the new generation of EEG headsets. Neurable[6] is currently developing a new device that integrates EEG into the HTC Vice VR headset, and thus hopes to revolutionize human-computer interaction. Future research on BCIs in VR will consequently give rise to many new applications that previously were not possible. Additionally, the experiment revealed that a virtual reality video game can actively promote relaxation, if relaxation is directly included as a game mechanic. These findings contribute to the development of brain-computer interfaces and VR games or environments that serve a therapeutic purpose. Recent research shows the immense potential of channeling the ability of BCIs to assist meditation with neurofeedback. Using VR to visualize and augment the experience of meditation appears to be very effective. Because of the therapeutic power of meditation for various conditions, including ADHD, this technology might assist millions of users to start their recovery.

[6] http://www.neurable.com/

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Appendix A: Consent form

The purpose of this study is to test a VR game as a potential tool to stimulate relaxation.
In the following experiment you will first get acquainted with the virtual environment, after which you will be asked to play 2 versions of a video game for 5 minutes each. During this your brain activity will be recorded using an EEG headset. After each session you report your experiences on a short questionnaire. In total this should take around 1 hour of your time.
If you have had previous problems with Motion Sickness please inform the researcher.
The Virtual Reality environment might cause temporary motion sickness in some people. Therefore, you have the right to withdraw from the experiment at any time (for whatever reason), without any negative consequences for doing so.
All your data will be treated completely anonymously and will not be shared with any other party.

Should you have any further question about the research or your rights as a participant, don't hesitate to email lucasgord94@gmail.com

____________________ ____________________
Signature Participant Signature Researcher

____________________ ____________________

Appendix B: Game Experience Questionnaire (Poels, de Kort, & Ijsselsteijn, 2007)

Please indicate how you felt while playing the game for each of the items, on the following scale:

not at all	slightly	moderately	fairly	extremely
0	1	2	3	4
< >	< >	< >	< >	< >

1 I felt content
2 I felt skilful
3 I was interested in the game's story
4 I could laugh about it
5 I felt completely absorbed
6 I felt happy
7 I felt tense
8 I felt that I was learning
9 I felt restless
10 I thought about other things
11 I found it tiresome
12 I felt strong
13 I thought it was hard
14 It was aesthetically pleasing
15 I forgot everything around me
16 I felt good
17 I was good at it
18 I felt bored
19 I felt successful
20 I felt imaginative
21 I felt that I could explore things
22 I enjoyed it
23 I was fast at reaching the game's targets
24 I felt annoyed
25 I was distracted
26 I felt stimulated
27 I felt irritable
28 I lost track of time
29 I felt challenged
30 I found it impressive
31 I was deeply concentrated in the game
32 I felt frustrated
33 It felt like a rich experience
34 I lost connection with the outside world
35 I was bored by the story
36 I had to put a lot of effort into it
37 I felt time pressure
38 It gave me a bad mood
39 I felt pressured
40 I was fully occupied with the game
41 I thought it was fun
42 I felt competent