Hybrid Control and Game Design for BCI-integrated Action FPS Game

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***Abstract*— Despite years of research, the fundamental issues of Electroencephalography (EEG) remain one of the most prominent problems for Brain-Computer Interface (BCI) game design, resulting in BCI games that look very lacking compared to other games in the market. This paper presents a new hybrid game control that is a combination of 4 methods of interaction: a Steady-State Visually Evoked Potential (SSVEP)-based BCI that utilizes a state-of-the-art Riemannian-based classifier, a mouse, a keyboard and an eye tracker. This paper also presents an action First-Person-Shooting (FPS) game that works together with the control to deliver satisfying BCI game experience. This game features 3 mechanics that assist the BCI control: slowing down time, highlighting an SSVEP stimulus that is being looked at and activating an SSVEP command automatically if players fail to do so in exchange for not receiving some rewards. From the test result from 10 subjects, we found that all subjects can issue commands through the eye tracker adequately at first, but the performance degraded over time. SSVEP commands had a 60.5% successful manual activation rate and it took around 3.569 seconds for each successful manual activation. Despite some inconveniences seen from the result, 90% of the subjects still found the game enjoyable, and 10% felt neutral toward the game.**

Keywords-BCI; EEG; SSVEP; Games; Riemannian-based classification.

I. Introduction

Brain-Computer Interface (BCI) gives us a mean to control a computer without moving by monitoring our brain activity. There are several techniques used to monitor the brain activity, and one of them is Electroencephalography (EEG) [1]. EEG monitors the brain activity through electrodes mounted on the scalp, so the procedure is completely non-invasive and can be applied repeatedly to anyone without risks or limitations [2]. These advantages, combined with the ease of setting up offered by dry electrodes, make EEG-based BCIs undoubtedly the most suitable BCIs for gaming application.

BCI games have a lot of benefits. They can be used to help patients recover from incidents of stroke and traumatic brain injuries, treat seizure disorders, help children and adolescents who have Attention-Deficit and Hyperactivity Disorder (ADHD) [3] or improve the quality of life of people with severe disabilities. Even for normal players, BCI games can provide Neurofeedback (NF) functionality that can modify the game experience to best suit players' emotional state and improve players' attention and cognitive skill when played regularly [4]. However, the gaming industry has never adopted BCIs in any full-featured game [5] since it has fundamental issues that make it not viable compared to the traditional input devices. The first issue is that the number of commands available for players can be very limited, depending on the approach we choose to process EEG. Another issue is high intersubject variability which leads to unreliability, the need for calibration and the phenomenon called BCI illiteracy, which prevents some people from using a BCI effectively [1].

Among several EEG-based BCI approaches, one of the most reliable ones is Steady-State Visually Evoked Potential (SSVEP) [3]. This approach uses visual stimuli that flicker at the frequency of 6 Hz or above to evoke brain responses [6]. EEG at the same frequency and its harmonics will become very dominant and easy to detect once subjects start focusing on a stimulus, and it will continue to dominate as long as subjects continue focusing. This means that SSVEP can support many commands, can support continuous input, has high susceptibility to artifacts [5], requires little to no time for calibration [7] and has a low chance to find a subject with BCI illiteracy [1]. However, this approach comes with a few issues. The first issue is that it cannot control in-game movement efficiently [5]. The second issue is that the accuracy of SSVEP classification has never been perfected and will only diminish the more stimulus frequencies are being used [8]. The last issue is that each subject's reaction toward the stimuli can be wildly different. Some people, especially the elderly, can find them annoying [1] while some people can find them tiresome or uncomfortable after constantly looking at them [9]. The most extreme case is that it can trigger a seizure in people with epilepsy, so every test requires a subject's medical history checking beforehand [10].

Using an SSVEP-based BCI with other input devices can mitigate some of the issues. For example, the study by Stawicki et al. [8] shows that a spelling application controlled by an SSVEP-based BCI and an eye tracker works better than the same application controlled by the BCI alone. Unfortunately, this idea has not gained a lot of traction in BCI game research community yet [5].

For the reasons mentioned above, we developed a new hybrid game control that uses an SSVEP-based BCI, a mouse, a keyboard and an eye tracker together. We also developed an action First-Person-Shooting (FPS) game that features several mechanics to facilitate the BCI control. Both work together to bring BCI game experience closer to the game experience provided by other games in the market.

This paper is organized into 6 sections. Section 2 describes the EEG signal acquisition and the development of the signal processor. Section 3 describes the design and development of the game. Section 4 describes the procedure of the experiment. Section 5 presents the result and discussion before Section 6 finally concludes this paper.

II. BCI APPROACH

A. Signal Acquisition

EEG signals are acquired through G.SAHARA active dry electrode system and G.MOBILAB+ from G.TEC [11]. Since SSVEP can be detected strongly in the occipital region of the brain [6], the electrodes were mounted at the following positions according to the international 10-20 system: Oz, O1, O2, POz, PO3, PO4, PO7 and PO8. The electrodes are connected to G.MOBILAB+ which is responsible for acquiring EEG signal at the sampling rate of 256Hz.

B. Signal Processing

According to the report on the progress of BCI games by Kerous et al. [5] and our survey, we found that the SSVEP classification method usually used in later studies is Canonical Correlation Analysis (CCA)-based classification. However, in the updated review of classification methods by Lotte et al. [12], we found another type of method called Riemannian-based classification. This type of classification can be applied to several BCI approaches and gives a performance that rivals or even surpasses the previous state-of-the-art method. For SSVEP, the first implementation was proposed by Kalunga et al. [13], and the result showed that it can outperform 2 CCA-based state-of-the-art methods proposed by Lin et al. [14] and Nakanishi et al. [15].

This classification method involves mapping a band-passed signal directly onto a Riemannian manifold and using Minimum Distance to Riemannian Mean (MDRM) algorithm to classify the signal. Essentially, this means estimating a covariance matrix from the band-passed signal, then finding the distance between the covariance matrix and the matrices that represent each class before finally classifying the signal into the closest class. The representative matrices are derived from all covariance matrices in the same class during a training phase. There are 3 variations of the method presented in the paper. The first one does not use the full MDRM algorithm, trading accuracy for speed. The second one uses the full algorithm, trading some speed for accuracy. The last one uses the full algorithm and an outlier signal removal method called Riemannian potato for maximum accuracy. We chose the first one to make our BCI as responsive as possible and compensate for the accuracy by limiting the number of stimulus frequencies to only one and utilizing an eye tracker to determine what stimulus is being focused on instead. This can mitigate the error that can happen during SSVEP classification, which, in turn, improves the accuracy and reliability of our BCI significantly, as seen in the work of Stawicki et al. [8].

We chose to implement this classifier on Matlab [16]. The original work by Kalunga was not implemented for real-time applications as it uses 4 seconds of signal for each iteration and requires 5 iterations before it can give a definite answer. Since G.MOBILAB+ uses a 256Hz sampling rate, 4 seconds of signal means 8,192 samples (1,024 x 8 channels) which is too much for real-time processing, so we reduce it to 2.5 seconds. We do not want to reduce it any further as requiring a lot of data might be the characteristic of this classifier. Still, 5,120 samples remain a lot for real-time processing, so we decided to give Matlab 0.25 seconds to complete each iteration. We also remove the voting process completely and reassign that task to the game instead. This allows the game to dynamically adjust the voting process to suit the current context, which can be very beneficial for continuous input.

III. GAME APPROACH

A. Game Design

To demonstrate that the new hybrid control has more capability and imposes less restriction on the game design, we design the game with 2 goals in mind. First, the game must feature every kind of command that has ever been in an FPS game. Second, the game must feature unique mechanics to facilitate the BCI control that cannot be implemented with non-hybrid BCI control.

The core gameplay of FPS games is always the same since its earlier days, namely, players must progress through levels/maps and kill enemies. The innovation for the genre in terms of control comes from expanding more on this core gameplay. Regarding progressing through levels/maps, the most basic things that players need are movement, environment interaction and resources. In old games like Doom (1993) [17], movement is limited to walking and jumping, environment interaction is just pressing the right door switch, and resources only come in the form of pickups scattered around a level that can be utilized only when players walk right through them. However, in modern games like Far Cry 5 [18], movement can be sprinting, crouching or sliding, environment interaction can be talking to someone to receive a side quest, and resources can be items stored in the inventory that can be utilized anytime. Regarding killing enemies, the most basic things that players need are weapons. In Doom (1993) [17], players can only kill enemies with guns. However, in newer games like Borderlands [19], players can also kill enemies with a melee attack, a throwable item like a grenade or the special ability of the character that they chose.

Every command we have mentioned can be categorized into 5 types: movement, weapon, environment interaction, item and ability. Item and ability can be combined into one type since not every item and ability is meant for taking out enemies and both of their usages are limited by either quantity, cooldown or mana point. The real fifth type comes from in-game menu which is mandatory for every game. These 5 types are more than enough to serve the core

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gameplay of progressing through levels/maps and killing enemies. Therefore, they are enough for any FPS game.

Which command can be activated by SSVEP depends on whether or not it has at least one Head-Up Display (HUD) associated with it. However, as stated in the downsides of SSVEP, making every HUD become stimuli can be very annoying or tiresome for some players. Therefore, we need to do that only for the commands that require continuous input or the commands that do not, but should, require some degree of focus to activate. For the rest of HUD-associated commands, we decided to have players activate them by looking at a HUD and pressing a universal command button instead. The eye tracker that we use in this study is Tobii Eye Tracker 4C [20] which is capable of eye blink detection. This allows the game to know where players are looking at when they are blinking which can be translated into some additional commands as well.

The commands in movement type usually do not have any HUD associated with them. These commands should not require a lot of focus from players to activate as each of them is usually used in combination while players are focusing on more important tasks. Therefore, it is best to let players activate them easily through a mouse and a keyboard.

The second type is weapon which usually comes with a HUD: a crosshair for shooting or aiming down sight, an ammo count for reloading, a weapon icon for changing weapon, etc. We decided that aiming down sight should be activated by closing one eye to imitate how we aim a gun in real life. The rest of the commands, except shooting, can be activated by looking at a HUD and pressing a universal command button. Shooting is an exception because it shares the same HUD with aiming down sight and it needs both single and continuous input for automatic and semi-automatic weapons. Therefore, our solution is to make the command able to be activated by 2 methods: aiming at an enemy or focusing on a stimulus. The game also needs to slow down time for players when they are trying to focus because this command is more likely to be used during a hectic situation which can make focusing a lot harder.

The third type is item/ability, which needs a HUD to inform players whether an item/ability is available to use or not, meaning that every command in this type can be activated by looking at a HUD and pressing a button. However, we thought that there needs to be another way to activate these commands. Since some items/abilities tend to be used more often than others, having players closing one eye a little longer than usual to use the most essential item/ability immediately without the need to look at any specific HUD might improve gameplay significantly.

The fourth type is environment interaction, which needs a HUD to avoid confusion since most objects, or even doors, in most games are non-interactable. We decided that there should be 2 methods to activate this command: looking at a HUD and pressing a button or focusing on a stimulus. The latter would be used to depict an object that requires some effort to interact with. This also requires the game to slow down time for players if the interaction happens during a hectic situation.

The last type is in-game menu, which consists of every command related to in-game menus such as a pause menu, an inventory, a map, a weapon wheel, etc. We decided that it is best to let players control every in-game menu, except the weapon wheel, with a mouse and a keyboard since they can be wildly different in each game. The weapon wheel is an exception because its functionality is always the same; open, select an option and close which can be easily translated into holding a button, looking at an option before releasing the button.

From what we have described, a mechanic that facilitates the BCI control has already been mentioned, slow motion. This mechanic can already satisfy our goal since it needs an eye tracker, making it unable to be implemented with non-hybrid BCI control. However, due to the high intersubject variability of BCIs [1], we decided to add 2 more mechanics to improve the reliability, automatic activation and reward for manual activation. The game will activate an SSVEP command automatically at the end of the slow motion and give players some rewards if they can activate the command manually before the slow motion ends.

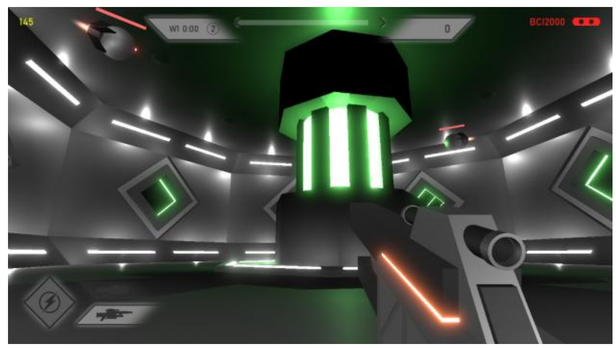

Figure 1. The screenshot of our game, Core Defender.

When combining this mechanic and the activation methods we have summarized together, we came up with a single-player FPS game called Core Defender, as seen in Figure 1. In this game, a player must use everything at his/her disposal to fight off 3 waves of enemies that want to crash into the core in the middle of the room. There are 2 weapons available: an assault rifle and a sniper rifle. The assault rifle can change between 3 ammo types: red ammo that does well against red enemies, yellow ammo that does well against yellow enemies and orange ammo that does well against both. If the player uses red or yellow ammo against the correct enemies, the player will be granted bonus scores. The sniper rifle, on the other hand, has only one ammo type and grants the player bonus scores all the time. Its shot is so powerful that it can destroy any enemy in a single hit. Besides the weapons, the player can also use the ability to turn on a laser grid around the core and slow down time. Turning on the laser grid can help the player destroy every enemy near the core, but it is limited to 2 times throughout the game. Slowing down time lasts for 8 seconds and players must wait for a cooldown to use it again. This ability is essential because it must be activated every time before the player can fire the sniper rifle or turn on the laser grid. If the player can activate one of those commands before the ability ends, the game will reward the player with a faster cooldown. Between each wave, the player has a choice to repair the core in exchange for some scores or skip to the next wave immediately. Regardless of how well the player plays, the core's health will always be reduced at the end of each wave to raise the stake for the player who wants the highest scores possible.

From the gameplay we have described, we can list every command available and summarize how each of them can be activated as follows:

- Using a mouse and a keyboard: move, look, open/close the assault rifle mode selection menu (Figure 2).
- Aiming at an enemy: fire the assault rifle.
- Pressing a universal command button when looking at a specific HUD: change weapon, use/cancel slowing down time.
- Closing one eye: aiming down sight.
- Closing one eye longer than usual: use/cancel slowing down time.
- Focusing on a stimulus when slowing down time is active: fire the sniper rifle, activate the laser grid.
- Focusing on a stimulus when slowing down time does not have to be active: fix the core, skip the wait time between each wave.
- Looking: select an option in the assault rifle mode selection menu (Figure 2).

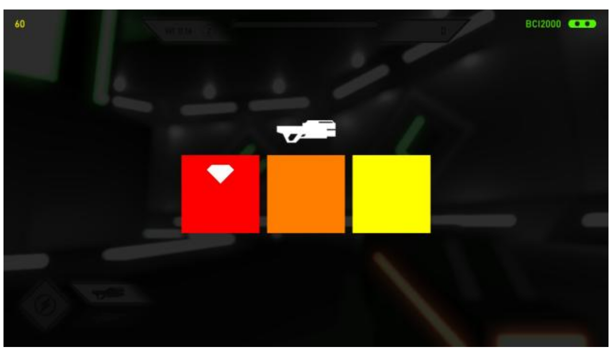

Figure 2. A screenshot showing the assault rifle mode selection menu.

B. Stimulus Design

Another thing that is crucial for bringing out the best performance of an SSVEP-based BCI is the stimuli. According to the report by Zhu et al. [21], using LED or fluorescent lights to display the stimuli can evoke stronger brain responses from a subject than using a monitor. Using a pattern reversal graphic instead of a simple flickering graphic can help us get a stronger brain responses as well. However, it is one of our goals to make the game as easy to set-up as possible and to make the stimuli look consistent with the rest of the game in terms of the aesthetic. Therefore, we cannot use those options which leaves us with 3 factors that we need to consider: frequency, color and visibility.

The frequencies used in most researches are usually in the range of 12-25Hz [21]. We decided to use 15Hz because, according to the study by Pastor et al. [22], the brain response reaches the greatest amplitude around this frequency.

The report by Zhu et al. [21] also wrote about the impact that stimulus color has on the performance of a BCI when using red, blue or yellow stimuli. However, none of those colors performs exceptionally well at 15Hz and the report stated that it required further study, so we chose the color that is used most among the studies that use the same type of graphic for their stimuli: white. The final design of our stimuli can be seen in Figure 3. Both second and third stimuli can appear at the same time.

Figure 3. The SSVEP stimuli that appear in the game.

Visibility is another factor that may become an issue in our study. Since the stimuli are white and displayed on a computer screen, they can be barely visible to the player when his/her in-game character is in a bright environment or looking directly at a light source. To solve this issue, we use a mechanic called stimulus highlighting, as seen in Figure 4. The game will utilize the eye tracker to darken everything on the screen except the stimulus that is being looked at.

Figure 4. A screenshot showing stimulus highlighting.

C. Game Development & BCI Integration

The game was developed on game engine Unity 5 [23] for Windows platform and was integrated with 2 other components: Tobii Eye Tracker 4C and signal processor.

The integration with Tobii Eye Tracker 4C was done through a low-level Software Development Kit (SDK) called Stream Engine SDK [24]. Even though there is Tobii Unity SDK [25] available, we cannot use it since it does not provide a crucial feature that is eye blinking detection.

The integration with the signal processor was done through a software suite called BCI2000 [26]. BCI2000 consists of 4 modules: a source module, a signal processing module, an application module and an operator module. The first 3 modules can be swapped in and out freely while the last one stays the same to make sure that those 3 modules work together properly. For the source and signal processing module, we use the modules that come with BCI2000 to receive the signal from G.MOBILAB+ and send it to our classifier in Matlab. For the application module, however, there is currently no module that can communicate with Unity directly, so we use a dummy application with the sole functionality of sending and receiving User Datagram Protocol (UDP) messages instead. These messages can be sent across 2 computers or sent to other programs on the same computer through the localhost address. Despite the performance overhead, we chose remote communication because it allows us to test the game anywhere by simply installing the game on a target computer.

IV. Experiment

The experiment was performed on 10 male subjects who had never been diagnosed with epilepsy. Most subjects' age ranged from 21 to 26, except 1 subject who was 46. The test environment was dimly lit to increase the effectiveness of SSVEP stimuli and contained as few electrical sources as possible to minimize the number of artifacts in the EEG signal.

The experiment consisted of 3 main steps. The first step was testing the eye tracker, which involved calibrating the eye tracker and testing every eye tracker-related command. The test was done by having a subject activate each command 10 times and report to us how many attempts it took to activate each of them. During this step, any commands that were triggered when the subject had no intention to use any commands would be recorded as false triggering. The second step was testing the BCI which involves mounting electrodes, calibrating the BCI and testing every BCI command. The test was done by having the subject activate each command 10 times before moving on to the next one. The time it took to activate each command or whether the subject activated it manually or not would be recorded by the game. The last step was playing which involved playing the game from start to finish at least once. The data about SSVEP activation that the game recorded would not contribute toward the BCI test result because, after a long test, we wanted the subjects to have fun with the game so they may not focus on the stimuli as hard when they did not feel the need to get faster slow-motion cooldown that manual activation provided. All subjects were told about the prize that they would receive if they won and got 80% of the possible score before the game started.

After the experiment was completed, every subject must do a questionnaire. This questionnaire is adapted from the core module of Game Experience Questionnaire developed by Poels et al. [27] which aims to assess game experience in 7 aspects: competence, sensory and immersion, flow, tension, challenge, negative affect and positive affect. Every question must be answered on a scale of 0 to 4; 0 means strongly disagree, 4 means strongly agree. The subject can also provide additional feedback if he/she wishes to do so.

V. Results and Discussions

A. Eye Tracker

Before the test began, we asked the subjects to close one eye to observe how well they can do it. Out of 10 subjects, there was only 1 who could keep the other eye open the entire time, which was below our expectation. Nonetheless, the result shows that the worst average first attempt rate of the commands that are activated by closing one eye is 70%, meaning that 70% of the time the subject can use the commands on the first attempt. The most attempts for a single command come from a different subject which is 3 attempts for aiming down sight. The worst average first attempt rate of the commands that do not involve closing one eye is 86.667%, and the worst false trigger rate is 7.407%. Overall, 10 subjects have an 86.5% average first attempt rate for the commands that are activated by closing one eye, a 96.333% average first attempt rate for the commands that are not and a 4.128% average false trigger rate. These data are enough to conclude that every subject can use eye tracker-related commands adequately during the test step.

TABLE I. The Result of the BCI Testing

	Shooting the Sniper Rifle			**Activating the Laser Grid**			**Skipping**			**Fixing the Core**			
	Manual	***Auto***	***Delay (sec.)***	***Manual***	***Auto***	***Delay***	***Manual***	***Auto***	***Delay***	***<8 sec.***	***>=8 sec.***	***Fail***	***Delay***
Sub. 1	7	3	1.764	5	5	2.41	4	6	2.421	6	2	2	2.792
Sub. 2	9	1	4.478	3	7	5.1	9	1	3.095	2	4	4	1.942
Sub. 3	9	1	4.042	7	3	2.355	10	0	3.542	8	0	2	2.265
Sub. 4	6	4	3.778	6	4	2.383	8	2	2.223	9	1	0	4.946
Sub. 5	5	5	3.045	8	2	2.531	7	3	3.684	8	2	0	3.992
Sub. 6	7	3	4.736	3	7	3.928	4	6	3.658	1	6	3	7.85
Sub. 7	6	4	2.752	5	5	3.703	8	2	2.669	6	4	0	3.672
Sub. 8	8	2	4.492	1	9	6.7	6	4	5.078	4	3	3	5.65
Sub. 9	7	3	3.088	2	8	1.992	6	4	2.808	2	5	3	5.567
Sub. 10	7	3	3.519	9	1	3.031	6	4	3.111	8	2	0	1.964
Avg.	7.1	2.9	3.569	4.9	5.1	3.413	6.8	3.2	3.229	5.4	2.9	1.7	4.064

B. BCI

The differences between the results of each command are far above our expectations. As seen in Table I, shooting the sniper rifle yields moderately good results with a 71% average manual activation rate and 3.569 seconds average activation time, while activating the laser grid and fixing the core are significantly worse. It is important to note that the activation time does not take Auto and >=8 sec. columns into account. We think that there are 3 potential causes. The first one is that the subjects might feel more pressured when trying to activate these commands. Activating the laser grid must be used during enemy waves, and the subjects must focus while they see enemies approaching from multiple angles. Fixing the core is a unique command because it has no automatic activation. Compared to other commands that have 8 seconds for manual activation, this command can fail completely if it is not activated manually within the time between enemy waves. The second cause might be the size of the stimulus which is noticeably smaller than the stimulus of shooting the sniper rifle. One subject also said that the position of the stimulus (upper screen) made it a bit harder to focus when compared to the stimulus of skipping that looks the same but is located in a different area (lower screen). The last cause, which we think affects every command in general, is the performance of the Riemannian-based SSVEP classifier. As mentioned before, this classifier in the original work requires 4 seconds of signal for each iteration. Applying that directly to our work might result in an average activation time that is well above 4 seconds. However, modifying the classifier to use only 2.5 seconds as we did might affect the accuracy and lower the manual activation rate, which is a trade-off that is worth looking into more in the future.

C. Playing Session

From 10 playing sessions, 453 enemies were destroyed in total, and 176 of them were destroyed by the sniper rifle which is equal to 38.852%. 60% of the subjects used the sniper rifle more than 40% of the time, and 50% of those used the sniper rifle more than the assault rifle. These results show that most subjects felt confident enough to use SSVEP commands during an action whether the BCI worked reliably enough or not.

TABLE II. THE RESULT OF THE QUESTIONNAIRE

	Avg. Score	Result (Positive/Negative)
Competence	2.8	Positive
Sensory & Immersion	3	Positive
Flow	3	Positive
Tension	2.3	Negative
Challenge	3.2	Positive
Negative Affect	1.42	Positive
Positive Affect	2.9	Positive

D. Questionnaire

We averaged the scores of every question in each category across every subject and the result can be seen in Table II. The max score of 4 can be either positive or negative, depending on the category. As can be seen, the subjects generally have positive impressions toward the game in every aspect except one, tension. The questions in the tension category focus on whether the subjects felt annoyed or frustrated by the eye tracker and BCI control or not. The average score of the eye tracker control is 2.1, and the average score of the BCI control is 2.5. When comparing the eye tracker score to the results of the previous test, it clearly shows that most subjects experienced facial fatigue during the real playing session. Despite all these negative results, most subjects still enjoyed the game and felt that they could control the game well enough, which are reflected in the positive affect and competence score.

VI. CONCLUSION AND FUTURE WORK

A new hybrid control, which is a combination of SSVEP-based BCI, an eye tracker, a mouse and a keyboard, has been presented. The BCI utilizes the Riemannian-based classifier proposed by Kalunga et al. [13] in the hope of making the BCI reliable enough to control FPS games. An action FPS game that features several mechanics to facilitate the BCI control has also been presented. Those mechanics are slow motion, automatic SSVEP activation, highlighting stimulus and reward for manual activation.

The performance of the BCI is inconsistent. The results were decent for some commands, but far below our expectation for others. This might be because we reduced the signal window used for each iteration from 4 seconds, as originally proposed, to 2.5 seconds. Furthermore, we found that most subjects cannot close one eye perfectly and experienced facial fatigue during the real playing session, which makes eye tracker-related commands more frustrating to use. Despite these issues, the mechanics of the game still helped the subjects gain enough control of the game to find it enjoyable and created enough incentive for the subjects to use BCI commands.

In future studies, we would like to focus on finding the optimal signal window that maintains both speed and accuracy for the classifier. We will also make activating commands by closing one eye not mandatory for aiming down sight since it is not related to the BCI and it hurts the overall game experience more than enhances it.

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