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ON A GAMIFIED BRAIN-COMPUTER INTERFACE FOR COGNITIVE TRAINING OF SPATIAL WORKING MEMORY

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ABSTRACT

In the United States, there are a large number of people suffering from memory and attention problems, for example, patients with attention-deficit hyperactivity disorder (ADHD) and dementia. People with these problems have difficulties in performing activities of daily living and have a low quality of life. Currently, there is no existing effective treatment for these memory and attention issues in specific cognitive impairments. In this paper, we developed a platform of gamified brain-computer interface (BCI) for cognitive training, which can engage users in the training and provide users qualitative and quantitative feedback for their training of spatial working memory. The user is able to control the movement of a drone using their sensorimotor rhythms, recorded by EEG. 20 normal healthy subjects were recruited to test the user experience. Our system showed the capability of engaging users, good robustness, user acceptability and usability. Therefore, we think our platform might be an alternative to provide more accessible, engaging, and effective cognitive training for people with memory and attention problems. In future, we will test the usability and effectiveness of the system for cognitive training in patients with ADHD and dementia.

Keywords: cognitive training; gamification; brain-computer interface, spatial working memory

1. INTRODUCTION

Attention-Deficit Hyperactivity Disorder (ADHD) is a medical condition that affects approximately 6.1 million, or 9.4% of children in the United States according to a national parent survey conducted in 2016 [1]. Common symptoms of ADHD include difficulty in focusing on tasks, fidgeting, excessive movement, and forgetfulness, which interfere with daily functioning [1]. Recent studies have alluded to an association between ADHD and dementia where patients of both diseases exhibit similar general symptoms of memory and attention problems [2-6]. Dementia is an increasing problem in the United States due to the aging population, with an estimated 5 million adults suffering from dementia in 2014 [5]. Conventional treatments of ADHD include behavioral therapy and medications [1]. No such treatments exist yet for dementia [5]. In the past few decades, multiple studies demonstrated the insufficient efficacy of extant working memory training of ADHD [7, 8]. One hypothesis suggested that the discrepancy may reflect the inadequate targeting of the behavior of these disorders with regard to functional impairment with specific working memory (WM) components [9]. To enhance the effectiveness of working memory training, an adaptive design of working memory cognitive training in specific components for ADHD and dementia is required.

People with ADHD or dementia experience memory problems, particularly in the area of working memory, which is a cognitive area that helps with mental storage and manipulation of information in cognitive processes [10-12]. Two such areas of WM are visual working memory (visual WM) and spatial working memory (SWM). The former is concerned with static visual image manipulation, whereas the latter is concerned with movement and manipulation of dynamic information [13]. SWM and visual WM difficulties persist in those with ADHD and dementia.

Recently, the technology of Brain-Computer Interfaces (BCIs) is becoming a popular, promising approach for cognitive training/treatment. For example, it has been widely utilized for the treatment of ADHD [14]. BCIs record brain activity through various modalities (e.g., one leading modality of EEG or electroencephalogram) and interpret these signals to control a device through biofeedback [15]. Sensorimotor rhythms (SMR), including the mu frequency between 8 and 12 Hz, are one common signal that is used to assess brain activity [14]. Several studies have shown that EEG biofeedback can be used to improve attention skills and reduce impulsivity in children with ADHD [16-19]. Nowadays, BCIs have been utilized widely to sponsor passive evaluation approaches in the improvement of WM skills based on its peculiarity [20, 21]. However, the improvement of SWM using BCI approaches is still in an infancy stage.

Integrating gaming elements in cognitive training for mental health is not a novel approach. Multiple previous researches were focusing on the motivation functions in gamification which can be utilized in training mental diseases, specifically in ADHD [22]. Numerous studies have presented the gamified intervention as a promising technology in developing ADHD patients' engagement and motivation, along with other potential skills, in the cognitive training process. However, the lack of statistical evaluations in complex scenarios limits the efficiency of gamified cognitive training in medical treatments, as non-medical supplements [23].

Based on previous research, BCI is sufficient in defining and evaluating working memory performance based on the simulated cortex patterns [24, 25]. We herein proposed and developed a framework for a gamified BCI platform, which may be conducive to engage and improve the SWM skills in vulnerable populations with ADHD or dementia.

2. MATERIALS AND METHODS

The methodology of this approach is to design a BCI based gamified control development prototype to train patients with ADHD or dementia suffering from SWM impairments and to create a demonstration game to support future study. To achieve these goals, a potential gamified spatial working memory training task was designed. Multiple previous psychological studies in a non BCI environment of spatial working memory rehabilitation focused on designing training regime in a simulated 3-D environment to monitor and detect repetitions in two simultaneous streams of spatial information (spatial location and scene identity) [26]. The BCI based mind-controlled quadrotor drone platform was recognized as a potential candidate that could utilize a similar study design and 3-D environment as presented above in a real-world space area, but with the potential capability of more effectively improving SWM ability using BCI neurofeedback. Compared with previous studies, the mind-controlled drone can provide real-time feedback in real time, besides the passive feedback.

Conventional cognitive training (e.g. N-back paradigm) may not be efficient in working memory rehabilitation of ADHD or dementia. Murphy et al. [27] hypothesized that motor imagery practice may improve WM and showed that expert athletes are more proficient than amateurs at prioritizing specific contextual and motor-relevant information in order to anticipate opponents' offensive plays. This phenomenon indicated a possible interaction between motor imagery and SWM [28]. The evidence that motor imagery practice activates functional reorganization in neural systems with reduced activity in the dlPFC (WM center) also supports the hypothesis in a flank direction. However, few studies have examined the interaction between SMR and SWM. In this article, an approach of using motor imagery as the rhythm of SWM training was developed.

2.1 Hardware

To explore a convenient, portable and affordable prototype that can be utilized in daily cognitive training with enough capability to achieve expected performance, Emotiv Epoc+ and DJI Tello were selected to promote the prototype.

Emotiv Epoc+: Emotiv Epoc+ is a 14 channel EEG recording device produced by bioinformatics company EMOTIV based in San Francisco, CA [29]. The 14 electrodes (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4) are mainly located on the motor cortex regions which would be able to provide desired EEG information. Emotiv adopts saline soaked felt pads as the sensor materials which allows the user to easily wear and process the experiment. The bandwidth of 0.16-43Hz is abundant to collect EEG brainwaves of motor imagery signals.

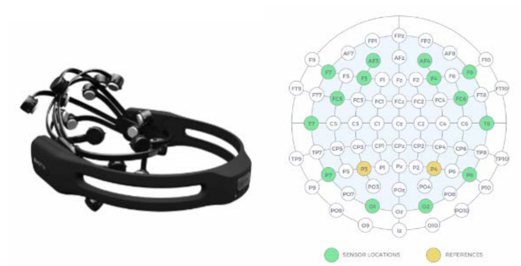

Figure 1. Emotiv Epoc+ (a) and its sensors and references locations (b); figures copied from [30].

DJI Tello: The Tello DJI is a highly cost-effective quadrotor drone with simple controls designed that allows children and aging people to use [31]. Suitable propeller guards ensure enough safety protection to demonstrate the mind-controlled drone around hazards.

2.2 Software

The purpose of this platform is to integrate the EEG recording device and the quadrotor drone. Two SDK software, EmotivBCI and TelloPy, were utilized in this platform.

EmotivBCI: The company EMOTIV implements a commercial software for BCI called EmotivBCI, which is suitable with Emotiv Epoc+. This software can be used to detect participants' cognitive state by trigger events. By using cognitive state records as the training set, real time tune applications can be applied in translating the state recordings into mind commands by their performance metrics [30].

In this platform, EmotivBCI was considered to collect participants' cognitive states in various SMR strategies, and transform the states recording to a pattern shown as the moving command (e.g., Push, Pull, Lift, Drop) which could then be sent to the quadrotor drone as the control command.

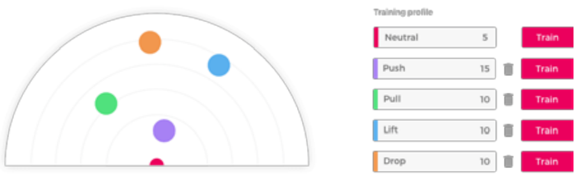

Figure 2. GUI of Emotiv BCI; figure copied from [30].

TelloPy: An SDK kit called TelloPy is developed for the DJI Tello quadrotor drone [27] that allows to promote applications of DJI Tello without using exogenous communication interfaces. The TelloPy connects drones by a Wi-Fi UDP port which allows users to send text commands from other devices.

These pieces of software contributed to the platform by processing the motor imagery cognitive status, transforming this status to drone adapted commands and sending/receiving text commands through UDP port.

2.3 Node-Red

Node-RED is an open source flow-based graphical user interface (GUI) to unify Internet of Things (IoT) hardware devices and Application Programming Interfaces (APIs) developed by IBM Emerging Technology [32]. Node-RED is built based on the Node.js platform and with a free JavaScript based structure to allow users to develop IoT interaction applications in a browser-based flow GUI editor. JavaScript Object Notation (JSON) is used to store Node flows which can control devices to process data, control other devices and send alerts [33]. This tool enables users to visually create real-time applications on end-devices.

EmotivBCI provides a Node-RED based custom library in the Node-RED Toolbox which enables users to create applications and integrations in a visual interface. The Node-RED Toolbox allows the EmotivBCI to send adapted commands via Wi-Fi UDP or TCP ports to Node-red to connect other end-devices which can receive commands.

In this platform, Node-red is used to interact between EmotivBCI and TelloPy by the UDP protocol. The information flow from Emotiv headset to the Tello drone is shown in figure 3.

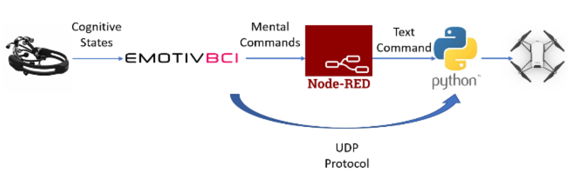

Figure 3: Illustration of information flow in the gamified BCI

2.4 Game Implementation

To accomplish the prototype of using sensorimotor imagery rhythms to control a drone for SWM cognitive training, two main designing protocols were required: spatial location detection and scene identity treatment.

Spatial location detection: In purpose of setting a circumstance for spatial location detection, the training was proposed to settle the target in a location of a 3-D environment. Reflecting on using the air drone as the target, we designed to allow the user to control the drone in an open space area to reach a predesigned location. To simplify the experiment and increase the safety, the participants can only control the drone in the vertical direction.

Scene identity treatment: SMR was applied to distinguish cognitive states and control the drone. Considering the cognitive capabilities of ADHD and dementia patients, a simple SMR strategy is essential in this prototype. Therefore, relaxation and imaging grabbing both hands were selected based on their significant cognitive states' disparities [34].

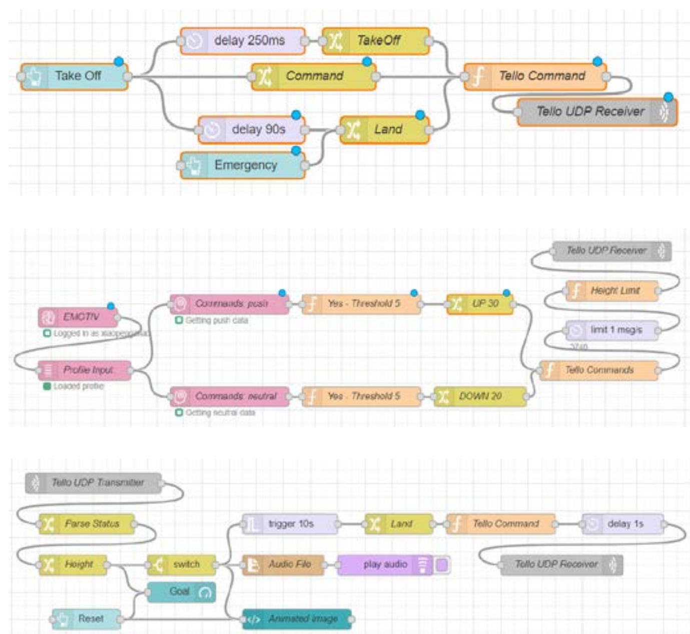

Figure 4: Node-Red GUI flow with different functions: (a) Drone's Take Off and Emergency command, (b) Connection between Emotiv Epoc+ headset and Tello drone, (c) Drone's Height measure and goal Achievement

To integrate two protocols, a drone would be controlled by the participant using their SMR. After the training process, the participant would be able to control the drone in the vertical direction by two states: Imaging grabbing both hands and relaxing. In the controlling process, when the participant is imaging grabbing both hands, the drone will fly up, and drop down otherwise. The participant is required to control the height of the drone by using this strategy until they reach the height which they were informed of at the beginning of the experiment.

As a competitive gamified cognitive training platform, the mind-controlled drone game was proposed to adjust the difficulty to keep the engagement and motivation of participants. To achieve this, the weights of SMR command activation threshold are adjusted based on the performance of user goal achievement. If the user achieves the settled location on time, the threshold of sending the flying up command will increase. Otherwise, the threshold of the relaxation command will decrease to continuously engage users in the cognitive training.

To implement the SMR training protocol, a Node-Red based GUI training application was designed. In the drone command function flow in Node-RED (as shown in Figure 4.a), two buttons: Take off and Emergency, were selected to defaultly control the drone to take off and land. In the ideal cognitive training process, the participant would press the takeoff button (as shown in Figure 5) to launch the drone. Count from the time of pressing the takeoff button, the participant would have 90 seconds to control the drone to the target height, or the drone would drop off after 90 seconds. An emergency button was used to drop off the drone immediately to keep the participant safe.

By utilizing EmotivBCI Node-RED Toolbox, two mental commands, push and neutral, which correspond to the grapping hands and relaxing imageries, would send from Emotiv Epoc+ to the Tello drone (as shown in Figure 4.b). When push (activated) or neutral command are activated, the mental command would transfer to raise the drone in 30 cm or lower in 20 cm, respectively. Two threshold values of both push and neutral commands were set for adjusting the activation level of both commands to control the difficulty of the training. A height limit of the drone flying range was selected for the safety concerns.

The flying height measurement system in the drone was used to estimate the goal of reaching height. As shown in Figure 4.c, the current height of the drone would send from the UDP port to the Node-Red and update whenever the drone is activated by the mental command. When the drone reaches to the desired height in time, the water jar shown in the GUI would be filled (as shown in the Figure 5), and the drone would land automatically. The GUI dashboard would then present an animated image and play an applause sound to encourage the participant.

Figure 5: GUI dashboard of the designed application

3. EXPERIMENTS AND RESULTS

3.1 Participants

Participants were recruited to test the effectiveness and user acceptance of the developed mind-controlled drone game. The recruitment was conducted through classroom announcements and flyers in the University of Tennessee, Knoxville, following the requirement of institutional review boards. Finally, 20 healthy adults (18-60 years, 12 males) participated in our experiments, with no history of neuropsychiatic disorders. All the participants were provided with a detailed description of the experimental goal and procedures before provided with written informed consent. They were also told that they could quit the experiments whenever they wanted, with no punishment. All the participants have normal or corrected-to-normal vision.

3.2 Experimental Setup

After signing the written informed consent, the participant will sit on a comfortable chair, in front of the computer screen. The observer will help the participants put on the EEG headset, ensuring a good comfortability and contact quality of at least 98% by using saline liquid and adjusting the position of electrodes. Furthermore, the participant is suggested not to make large body movements, to make sure there is consistent contact quality during the experiments. Then, the observer will open the software, EmotivBCI, and create an individual file for each participant, with a file name of the participant's name. Later the participant will be presented the GUI for training. Firstly, the participant will do the resting-state training five times, each of which lasts for 8 seconds. In the resting-state training, the participant will be guided to relax. Then the participant will perform the 8-second, action-state training five times, during which they will be presented with an interactive image. When presented with this image, the participant will imagine using their hands to pull/grasp the cube. Later, if the training goal has been achieved, the participant will directly go to the next stage, controlling the drone with their mind. Otherwise, the participant will be suggested to perform another action-state training.

During the stage of controlling the drone, the participant will be presented with a changing cylinder. They will be informed that the greater you imagine using your hands to pull an object, the greater the shaded area will become and the higher the drone will fly. If needed, the participants will be provided with encouraging information, such as, "Keep going! You're almost there!". After the participant achieves the goal, an animated image will appear as well as a sound for. However, if the participant cannot achieve the goal within 90 seconds, the drone will land automatically. After the experiments, the participants will be asked if they feel the movement of the drone is in their mind control.

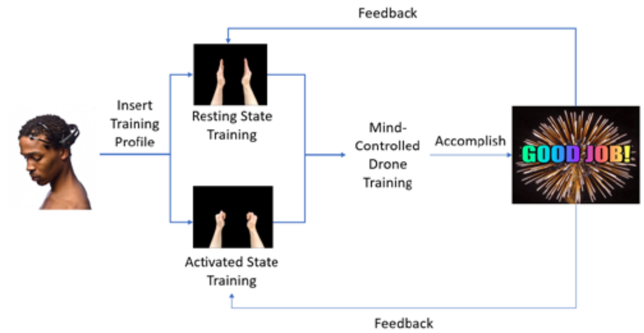

Figure 6: Illustration of experiment set up

3.3 Results

All the participants were amazed by and interested in this mind-controlled drone game. And most of them gave astounded feedback that they were controlling the drone's movement by using their mind, although some participants could not achieve the goal within 90 seconds.

Some single EEG data were recorded and analyzed as a sample, and the result reflects two significantly different patterns between the state of relaxation and imaging grabbing hands in mu frequency, as shown in Figure 7.

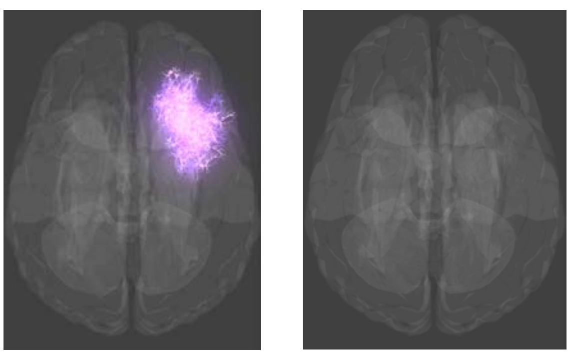

Figure 7: Cortex pattern examples in grabbing hands imagery and relaxing imagery

4. CONCLUSION

In this paper, we developed a mind-controlled drone game prototype for cognitive training and rehabilitation. We tested this system by designing and running a real-time training task, which will be utilized in processing the usability in an ADHD and dementia cognitive training environment. We have tested the BCI game on dozens of participants to ensure the acceptability, robustness, and positive user experience of the system. In future work, we will collect and analyze EEG records to study the efficacy and statistical significance of the game system in cognitive training. The next step of this project is to utilize this platform as an experimental tool to compare the cortex pattern in the training process between ADHD or dementia patients and normal people.

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