NeuralDrum: Perceiving Brain Synchronicity in XR Drumming

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Figure 1: The Neural Drum setup space (left), showing the first-person view during low (middle) and high (right) synchronization

ABSTRACT

Brain synchronicity is a neurological phenomena where two or more individuals have their brain activation in phase when performing a shared activity. We present NeuralDrum, an extended reality (XR) drumming experience that allows two players to drum together while their brain signals are simultaneously measured. We calculate the Phase Locking Value (PLV) to determine their brain synchronicity and use this to directly affect their visual and auditory experience in the game, creating a closed feedback loop. In a pilot study, we logged and analysed the users' brain signals as well as had them answer a subjective questionnaire regarding their perception of synchronicity with their partner and the overall experience. From the results, we discuss design implications to further improve NeuralDrum and propose methods to integrate brain synchronicity into interactive experiences.

CCS CONCEPTS

• **Human-centered computing → Collaborative and social computing design and evaluation methods**; *Mixed / augmented reality*.

KEYWORDS

hyperscanning, Virtual Reality, brain synchronicity

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1 INTRODUCTION

This paper describes an interactive game designed to increase brain synchronisation. When two individuals perform the same activity at the same time, sometimes their brain activity can become synchronised. This can be detected by hyperscanning, a neuroscience method where brain activity is simultaneously collected from two or more individuals [Montague et al. 2002]. Brain activity synchronisation has been observed in finger tracking tasks [Yun et al. 2012], card playing [Babiloni et al. 2007], flight simulation [Astolfi et al. 2011], and many other activities. When brain synchronization occurs, people are able to work together better [Toppi et al. 2016]. This shows that hyperscanning could potentially be a useful method to evaluate the effectiveness of collaboration when performing a specific task.

Although brain synchronisation has been observed in real world tasks, there has been very little research on tasks conducted in extended reality (XR) and human-computer interaction (HCI). Furthermore, most work rarely investigated if the synchronization of the brain signals can be perceived by the user. In this work, we present NeuralDrum, a VR-based drumming experience in which a pair of drummers play a drumming game, duirng which we perform hyperscanning on both of them using a headband that collects electroencephalography (EEG) signals. We then compute the phase locking value (PLV) from the collected EEG signals in real-time, which directly reflects their brain synchronicity level in the XR experience. The novelty of this work lies in the use of hyperscanning in XR and HCI, and understanding the perception of brain synchronicity. The goal of this work is threefold:

(1) Blending cognitive neuroscience methodologies with immersive VR experiences in a closed feedback loop.
(2) Understanding the ability of users to perceive brain synchronicity, both visually and auditorily.
(3) Introducing the use of hyperscanning for future collaborative XR and HCI related research.

2 RELATED WORKS

2.1 Brain Synchronicity

Hyperscanning was first introduced by Duane et al. [Duane and Behrendt 1965] who performed simultaneous brain signal measurement on twins and evaluated their connectedness. However, it was not until 2002 that the term was used, where hyperscanning was again performed on two individuals participating in an interaction game [Montague et al. 2002]. It was found that the interaction itself induced brain synchronicity measured with functional magnetic resonance imaging (fMRI). The synchronicity was observed from the activation of neurons from the same regions of the brain. However, the synchronization itself was not used to influence the game. Yun et al. [Yun et al. 2012] introduced phase-locking value (PLV) as an index of neural synchronicity. In their experiment, two participants were required to perform a fingertip synchronisation task, where one participant moves his/her finger around, and the other participant mirrors and follows the movement. Other examples of task performed during hyperscanning are between pilots in a flight simulator [Astolfi et al. 2011] and a card game [Babiloni et al. 2007], where both found high synchrony at the prefrontal area of the brain. However, these works simply measure the occurrence of brain synchronicity and not if the participants themselves are able to perceive it.

2.2 Collaborative VR Experiences

Virtual reality (VR) is an immersive platform that can accommodate multiple users in a shared virtual space, opening up many possibilities for collaboration [Wang et al. 2019]. The myriad of tools for input and interactions for VR [Sra et al. 2018], such as gesture recognition, sensory modalities, and physiological input further expands the possibilities for users to interact and communicate with each other. There has also been research on the use of physiological signals like heart rate feedback to directly affect shared VR experiences [Chen et al. 2017]. VR can blur the lines between gaming/entertainment and training/simulation due to actual physical movement that mirrors the task [Hajika et al. 2019].

NeuralDrum is more closely related to XR as opposed to just VR because the experience covers the transition between mixed reality (MR) to VR. The goal of NeuralDrum is to improve the collaborative experience in XR by using direct measures of the brain synchrony.

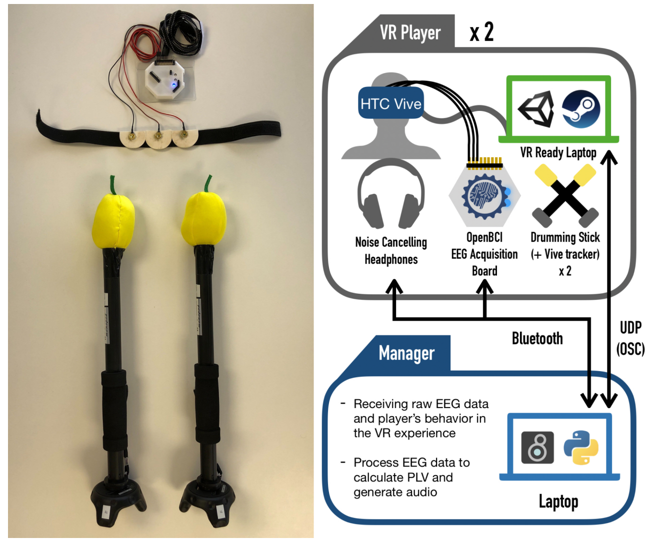

Figure 2: EEG headband and drum sticks used (left) with the system overview (right)

3 NEURALDRUM IMPLEMENTATION

3.1 EEG Sensing

To measure brain activity, each player wore a headband with three gold cap electrodes, which is connected to an OpenBCI EEG capture board, across their forehead. The setup is similar to that of Looxidlabs[1] that focuses on the forehead region for better electrode contact. This captures signals from the FP1 and FP2 locations in accordance to the standard 10-20 electrode placement [Oostenveld and Praamstra 2001]. We did not include any real-time motion artifact removal because the motion of the participants is what drives the signal synchronicity. We did however, request participants to keep their facial expressions relatively stable to reduce the impact of electromyography (EMG) signals from contaminating the EEG signals. We focus on the Theta band (4.0 to 7.9 Hz) because it has been reported that it indicates arousal, drowsiness and mental load prominently in the frontal lobe [Xie et al. 2016]. The reference electrode is pinned to the left earlobe. We used a sliding window of 500 samples and applied a band-pass filter to separate the Theta band signal from the other brain activity bands. From there, we calculated the PLV score for the FP1 and FP2 channels from both the participants. The PLV score ranges from 0.0 to 1.0, signifying the synchronicity of the input data.

3.2 XR Environment

Our XR environment was built with the Unity game engine[2], and viewed in the HTC Vive[3] head mounted-display (HMD). To enrich the visual effects in the XR experience, we used an Intel D415 Depth Camera[4] to support particle effects. Compared to a webcam, a depth camera allows point cloud manipulation in 3D space for a more

[1] https://looxidlabs.com/looxidlink/
[2] https://unity.com/
[3] https://www.vive.com/us/
[4] https://www.intelrealsense.com/depth-camera-d415/

visually pleasing effect. When synchronization is low, the camera will be more clear to easily synchronize movements, whereas when synchronization is high, the vision becomes more obscured with each point cloud eliciting higher particle effects (MR transitions to VR). To provide a haptic sensation for drumming, we placed simple everyday objects on a table, with virtual drums overlaying them in the XR scene. For the drum sticks, we used monopods with a plush toy attached on the ends to dampen the impact when drumming. Each of the sticks had a Vive Tracker attached to measure the stick movement as shown in Figure 2(left). There were a total of 4 drums placed in front of each player.

3.3 Game Design

NeuralDrum was inspired by popular rhythm games like "Taiko No Tatsujin"[5] and/or Beat Saber[6], where the goal of the player is to hit designated objects in time with the music rhythm. In NeuralDrum, rings slowly fall on each drum depending on the beat of the music. When the ring touches a drum, the player needs to hit the drum. NeuralDrum then augments the visual and audio feedback depending on the generated PLV. The four parameters that are affected by the PLV value are 1) the skybox, 2) particle effects, 3) audio quality and 4) see-through behavior of the depth camera. The generated audio and PLV calculation is handled by a separate computer running the Max[7] software and Python Script, as shown in Figure 2(right). Max plays and sends over our custom designed audio whereas our Python script receives the signals from the OpenBCI EEG platform, pre-processes it, and calculates the PLV in real-time. Finally, both the audio and PLV score is streamed to Unity via the Open Sound Control (OSC) protocol.

4 STUDY METHODOLOGY

We conducted a pilot study during the Siggraph Asia 2019 XR demo for the public [Hajika et al. 2019]. Each participant was first required to fill a consent form stating that they are free to withdraw from their participation at will and that audio, video, and other signal recordings will be collected for further analysis and future publications. After a quick briefing, the participants put on the EEG headband, the HMD, noise cancelling headphones, and held the drum sticks on each hand. Since this was an uncontrolled experiment in a public space meant for the enjoyment of participants, we asked participants to overall maintain a stable facial expression and avoid speaking to minimize artifacts.

The participant played the game by hitting the drums matching the falling of the rings, while an experimenter played the role of the second player who mirrored the motion of the participant. For example, if the player hit the left most drum with his/her left hand, the experimenter would hit the right most drum with his/her right hand. Since the participant is able to view the experimenter more clearly at low synchronicity, motion mirroring becomes easier, thus leading to higher PLV and more immersive visualization. This creates a closed feedback loop where the participant's PLV influences the game, which in return influences the PLV. At the end of the 5 minute demo, each participant answered a modified 7-point Likert Scale subjective questionnaire [Kim et al. 2014] shown in Table 1, as well as provide their qualitative feedback.

[5] https://www.bandainamcoent.com/games/taiko-no-tatsujin-drum-n-fun
[6] https://store.steampowered.com/app/620980/Beat_Saber/
[7] https://cycling74.com/products/max

Table 1: Likert Scale Questionnaire

Q#	Statement
Q1	I felt connected with my partner
Q2	I felt present with my partner
Q3	My partner was able to sense my presence
Q4	I enjoyed the experience
Q5	I was able to focus on the task activity
Q6	I am confident that we completed the task well
Q7	My partner and I worked together well

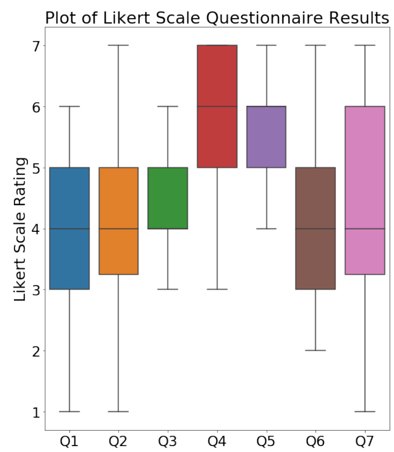

Figure 3: Questionnaire results

5 RESULTS AND DISCUSSION

A total of 40 participants data were collected, which was then reduced to 26 (15 males, mean:31.15, SD:10.94) due to software logging issues and/or excessively noisy signals. The results from the questionnaire are plotted in Figure 3. Q4 and Q5 earned the highest average score of 5.4 and 5.325 respectively.

We also document some of the feedback gathered from the participants. Some positive feedback include P4:"*This gives a fresh new idea on how experience can be synchronized, especially for solving a problem or accomplishing a task together*", P9:"*It has a meditative effect and I felt super relaxed while experiencing this. I had a really great time and nearly forgot I was drumming with a partner. I also felt connected to the universe*" and P22:"*It's quite interesting, I actually felt like my body was exchanged with my partner.*"

Regarding constructive feedback, P8:"*Needs louder sound when hitting the drums at the correct timing, less distracting particles, clearly show which drums are mine and which are my partner's*" and P10:"*Don't make the screen darker when the brains are not synchronized, and make the overall synchronization feedback clearer.*"

An example of the raw PLV for a good and bad player are shown in Figure 4 with the green regions indicating both players are hitting the same drum positions on their sides. We found that bad

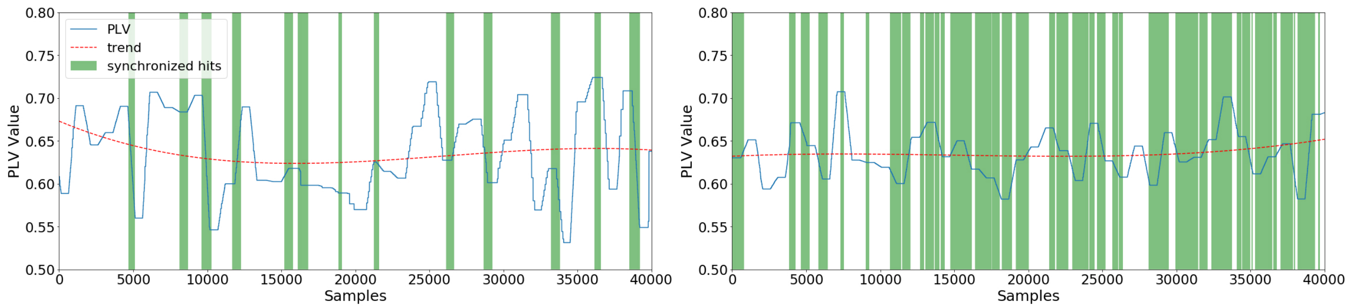

Figure 4: Sample plot of raw PLV between a participant who performed poorly (left) and well (right)

players had a more erratic plot and bigger dips in the PLV, with an overall negative trend throughout the duration of the game. For a good player, the PLV was relatively more consistent with an overall positive trend, although further testing is necessary to scientifically validate this. Furthermore, not all participants elicit the same pattern and further studies are required to determine the cause.

From the questionnaire results and some of the feedback gathered, we found that synchronicity was not easily perceivable by the participants (Q1, Q2 and Q3). We think this could also be due to how the game is designed, which required concentration to perform well causing the players to focus on the game itself and less on the visualization and audio feedback (Q5). Even though there were players who scored high for Q1, this varied greatly between participants, which in our opinion, makes sense because the generated PLV was based on EEG signals, which were directly effected by a person's attention, motivation, mental state, and so on [Kleih and Kübler 2015], especially for our uncontrolled.

6 LIMITATIONS

The currently available low cost EEG sensors today are susceptible to noise, especially motion artifacts (the combination of EMG signals and non-physiological noise such as cable movement) when coupled with a task in XR. This leads to a PLV score that could be inaccurate. Motion however, plays a key role in NeuralDrum and it is the effect of synchronous motion that eventually leads to brain synchronicity. Furthermore, as the study is conducted in public space, contamination in the signal is largely unavoidable. In the future, we will look into light motion artifact filters that still allow PLV monitoring in real-time, while preserving the EEG signals, such as adaptive filters [Jiang et al. 2019]. Additionally, the obtained results could be biased due to most of the attendees of the event and participants of the demo being possibly more technologically inclined. As mentioned before, synchronicity is affected by various other factors, and this could possibly affect it as well. A controlled environment would be useful for further analysis on synchronicity.

7 CONCLUSION

We present NeuralDrum, an XR drumming game where the experience of the players was directly affected by their brain synchronicity. We found that connectedness was not easily perceivable and the PLV consistency of participants seems to be affected by their performance. For future works, we will further look into the variables that effects the users perception towards brain synchronicity in a more controlled environment.

REFERENCES

Laura Astolfi, Jlenia Toppi, Gianluca Borghini, Giovanni Vecchiato, R Isabella, F De Vico Fallani, Febo Cincotti, Serenella Salinari, Donatella Mattia, B He, et al. 2011. Study of the functional hyperconnectivity between couples of pilots during flight simulation: An EEG hyperscanning study. In *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2338–2341.

Fabio Babiloni, Febo Cincotti, Donatella Mattia, F De Vico Fallani, Andrea Tocci, Luigi Bianchi, S Salinari, MG Marciani, A Colosimo, and Laura Astolfi. 2007. High resolution EEG hyperscanning during a card game. In *2007 29th annual international conference of the ieee engineering in medicine and biology society*. IEEE, 4957–4960.

Hao Chen, Arindam Dey, Mark Billinghurst, and Robert W Lindeman. 2017. Exploring the design space for multi-sensory heart rate feedback in immersive virtual reality. In *Proceedings of the 29th Australian Conference on Computer-Human Interaction*. ACM, 108–116.

Thomas D Duane and Thomas Behrendt. 1965. Extrasensory electroencephalographic induction between identical twins. *Science* (1965).

Ryo Hajika, Kunal Gupta, Prasanth Sasikumar, and Yun Suen Pai. 2019. HyperDrum: Interactive Synchronous Drumming in Virtual Reality using Everyday Objects. In *SIGGRAPH Asia 2019 XR*. ACM, 15–16.

Xiao Jiang, Gui-Bin Bian, and Zean Tian. 2019. Removal of artifacts from EEG signals: a review. *Sensors* 19, 5 (2019), 987.

Seungwon Kim, Gun Lee, Nobuchika Sakata, and Mark Billinghurst. 2014. Improving co-presence with augmented visual communication cues for sharing experience through video conference. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 83–92.

Sonja C Kleih and Andrea Kübler. 2015. Psychological factors influencing brain-computer interface (BCI) performance. In *2015 IEEE International Conference on Systems, Man, and Cybernetics*. IEEE, 3192–3196.

P Read Montague, Gregory S Berns, Jonathan D Cohen, Samuel M McClure, Giuseppe Pagnoni, Mukesh Dhamala, Michael C Wiest, Igor Karpov, Richard D King, Nathan Apple, et al. 2002. Hyperscanning: simultaneous fMRI during linked social interactions.

Robert Oostenveld and Peter Praamstra. 2001. The five percent electrode system for high-resolution EEG and ERP measurements. *Clinical neurophysiology* 112, 4 (2001), 713–719.

Misha Sra, Ken Perlin, Luiz Velho, and Mark Bolas. 2018. Novel interaction techniques for collaboration in VR. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, W33.

Jlenia Toppi, Gianluca Borghini, Manuela Petti, Eric J He, Vittorio De Giusti, Bin He, Laura Astolfi, and Fabio Babiloni. 2016. Investigating cooperative behavior in ecological settings: an EEG hyperscanning study. *PloS one* 11, 4 (2016), e0154236.

Peng Wang, Shusheng Zhang, Xiaoliang Bai, Mark Billinghurst, Li Zhang, Shuxia Wang, Dechuan Han, Hao Lv, and Yuxiang Yan. 2019. A gesture-and head-based multimodal interaction platform for MR remote collaboration. *The International Journal of Advanced Manufacturing Technology* 105, 7-8 (2019), 3031–3043.

Jun Xie, Guanghua Xu, Jing Wang, Min Li, Chengcheng Han, and Yaguang Jia. 2016. Effects of mental load and fatigue on steady-state evoked potential based brain computer interface tasks: a comparison of periodic flickering and motion-reversal based visual attention. *PloS one* 11, 9 (2016), e0163426.

Kyongsik Yun, Katsumi Watanabe, and Shinsuke Shimojo. 2012. Interpersonal body and neural synchronization as a marker of implicit social interaction. *Scientific reports* 2 (2012), 959.