Connecting the Brains via Virtual Eyes : Eye-Gaze Directions and Inter-brain Synchrony in VR

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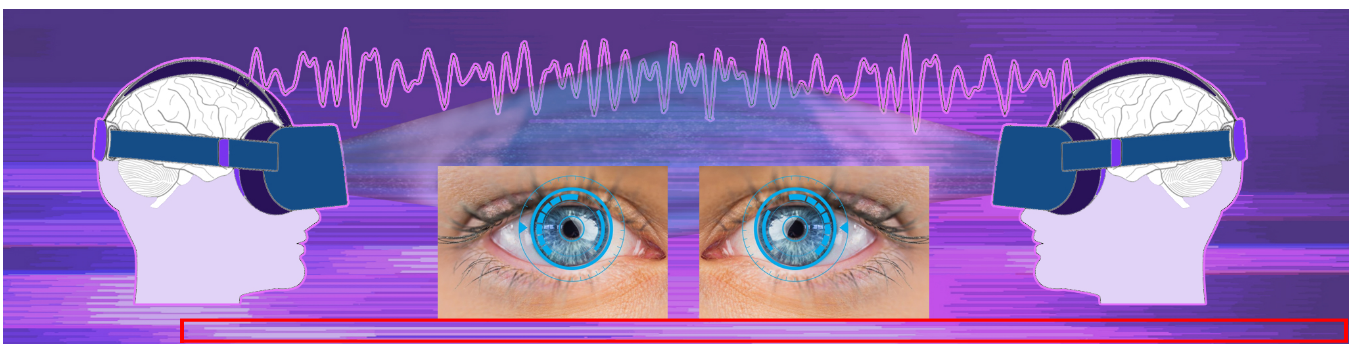

Figure 1: Inter-brain synchrony in relation to various eye-gaze directions in VR

ABSTRACT

Hyperscanning is an emerging method for measuring two or more brains simultaneously. This method allows researchers to simultaneously record neural activity from two or more people. While this method has been extensively implemented over the last five years in the real-world to study inter-brain synchrony, there is little work that has been undertaken in the use of hyperscanning in virtual environments. Preliminary research in the area demonstrates that inter-brain synchrony in virtual environments can be achieved in a manner similar to that seen in the real world. The study described in this paper proposes to further research in the area by studying how non-verbal communication cues in social interactions in virtual environments can affect inter-brain synchrony. In particular, we concentrate on the role eye gaze plays in inter-brain synchrony. The aim of this research is to explore how eye gaze affects inter-brain synchrony between users in a collaborative virtual environment.

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CHI '21 Extended Abstracts, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8095-9/21/05…$15.00
https://doi.org/10.1145/3411763.3451583

CCS CONCEPTS

• **Human-centered computing** → **Computer supported cooperative work**.

KEYWORDS

Hyperscanning, Eye gaze, Remote collaboration, Brain synchronization, Inter-brain synchrony, Virtual Reality (VR)

ACM Reference Format:
Ihshan Gumilar, Amit Barde, Ashkan F. Hayati, Mark Billinghurst, Gun Lee, Abdul Momin, Charles Averill, and Arindam Dey. 2021. Connecting the Brains via Virtual Eyes : Eye-Gaze Directions and Inter-brain Synchrony in VR. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '21 Extended Abstracts), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3411763.3451583

1 INTRODUCTION

Social interactions form the bedrock of the human condition. Without them, everything we see around us ceases to exist. Our entire lives, and the world we inhabit is predicated on our abilities to interact with each other. This has demonstrated, more than ever, the irreplaceable role of social interactions have in our personal and professional lives. But, it has also shown us that these interactions tend to change significantly when carried out via a facilitating medium such as video conferencing. Video conferencing, among others methods, has demonstrated significant increase in usage over the last year [33]. It has been the preferred method for work and casual social interactions [33, 40]. A small section of the population also used platforms such as AltSpace[1] and Mozilla Hubs[2]. However, despite having access to these forms of real-time communication, a major drawback with these platforms has been their inability to replicate face-to-face communication. This has lead to sense of 'detachment' between people participating in these online interactions.

Social interactions and communication between people have been studied for a long time [12, 21, 41]. Since the advent of video conferencing, many researchers have studied how this form of remote interaction between two or more individuals affects their sense of presence and the feeling of connectedness with each other [26, 27, 46, 54]. A large portion of the research in these areas has relied on observations and questionnaires to identify certain aspects of social interactions. It must be understood that social interactions are made of a number of implicit and explicit communication cues. While explicit communication cues are easy to observe, record and interpret, it is widely believed that implicit cues such as micro-expressions, eye gaze and minute hand gestures provide a more accurate representation of the quality of social interactions. Another aspect to the study of social interactions has been the use of physiological sensors such as heart rate (HR) monitors, galvanic skin response and electroencephalography (EEG). Recent advances in technology now allow researchers to monitor the neural underpinnings of social interactions using synchronised EEG devices. For example, some studies have demonstrated synchrony between the neural activity of people undertaking collaborative tasks in the real-world [5, 38, 50]. These are some of the first studies to shed light on the neural underpinnings of collaboration. They have helped us begin to understand how social interactions between people work when these interactions are viewed as an exchange of information between two or brains.

[1]https://altvr.com/
[2]https://hubs.mozilla.com/

There have been studies that integrated EEG and VR [1, 4]. Moreover, given an increasing number of research on interactions between people in virtual environments (VEs), it is in our interest to explore how these environments affect the different aspects that make up social interactions, particularly on neural aspect. Our primary focus is the study on implicit cues that contribute to social interactions, using the EEG neuro-imaging technique. While there exists some work on the neural underpinnings of social interactions in VEs [8, 25], it is a largely unexplored area of research. This paper lays out some preliminary work being carried out in the role that eye gaze plays in social interactions in VR using the hyperscanning technique. Hyperscanning refers to the recording of neural activity from two or more people simultaneously [38]. The rest of this paper lays the work that has informed the study described later in the paper, the study design and some preliminary results.

2 BACKGROUND

As seen from the previous section, there are two aspects to the research that we plan to undertake. One is the study of collaboration in VEs, while the other is the use of neuro-imaging devices to monitor the interactions in a VE. The aim of monitoring the neural activity of participants in a collaborative VE is to determine if the brains of the participants 'sync up' during the process of collaboration. Remote collaboration in VEs has been the subject of research for close to three decades [20]. Research in the area has demonstrated that VEs are capable of facilitating remote-collaboration between users by immersing them in life-like environments. VEs can be designed to mimic every possible collaborative scenario that exists in the real-world. Additionally, the ability to alter visual perspective makes them an ideal platform to facilitate effective remote collaboration [36, 42]. Several aspects of remote collaboration in VEs and how they benefit users have been studied. A number of human factors have also been investigated in order to understand how interactions in VEs with other users in the environment and the environment itself function. Researchers have studied the effects of gaze [23, 43, 52], avatars [23, 42, 52] and other manifestations of bodily interactions both implicit and explicit [9] to understand how they affect interactions in VEs. Despite this research, there is a gap in our understanding of these mechanisms at a deeper level. We are yet to fully understand how these interaction mechanisms are reflected in the brain, and how we perceive and react to these in collaborative VEs. As stated in the earlier section, there is some work that has been undertaken to investigate the neural correlates of social interaction in the real-world [17, 56]. However, besides the study by Gumilar et al. [25] and Barde et al. [8], there appears to be no detailed study undertaken in a similar vein with respect to VEs.

Using EEG to monitor social interactions has a long history [19]. However, it has not been until recently with the advent of low-cost, high fidelity EEG headsets that this has been possible on a large scale. Social neuro-scientists have always been interested in studying the neural correlates of social interaction. In the last decade, the interest in social neuroscience in general and hyperscanning in particular has dramatically increased. Hyperscanning has been used in traditional lab settings and real-world task based scenarios to explore how human being interact in different social situations.

Studies ranging across the spectrum from adapted versions of the ultimatum game [53] and traditional card games [5] to those that seek to explore the collaboration between pilots of a commercial airline [56] have been run. However, the uptake of this methodology has been lacking in research that explores collaborative VEs. The primary use for EEG in this domain for close to a decade has been as a Brain-Computer Interface (BCI). BCIs mediate the interaction between a user and the computer by 'decoding' the neural activity [59]. While BCIs are not the focus of this research topic, it is important to note that they serve as the precursor to the implementation of hyperscanning in VEs. Before we proceed further, it is important to take a brief look at some of the work in hyperscanning that has informed our research direction. The following subsection provides some detail regarding the hyperscanning methodology, state of the art and the research gaps that exist in the field.

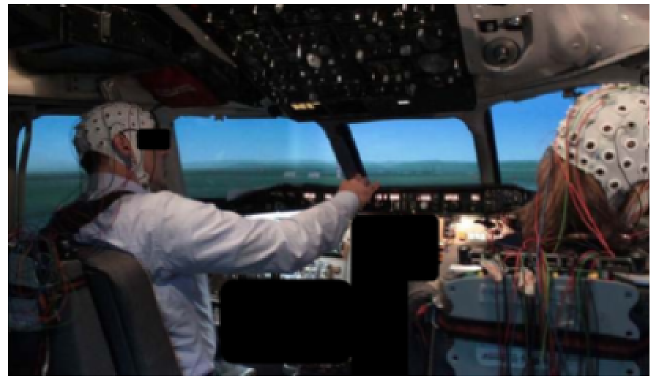

Figure 2: Hyperscanning in an ecologically valid environment [56]

Figure 3: Hyperscanning inside VR [25]

2.1 Hyperscanning

Hyperscanning refers to simultaneous recording of neural activity from two or more people [38]. Beginning with functional Magnetic Resonance Imaging (fMRI) [11, 16, 38, 47, 51], hyperscanning covers the entire spectrum of neural monitoring devices from EEG [2, 5, 15, 60, 61] to functional Near Infrared Spectroscopy (fNIRS) [39, 53]. However, the last decade or so has seen EEG devices being used for hyperscanning. This is because of the high temporal resolution that an EEG device is able to provide. Another factor has also been the decreasing cost coupled with an ever increasing quality of signals that EEG is able to provide. Over the years EEG hardware has evolved from an unwieldy, wired and hard-to-setup piece of equipment to a wireless and easy to use tool. Modern day EEG headsets allow researchers to carry out studies in real-world environments such as classrooms [16].

Hyperscanning studies have been carried out using a range of experimental paradigms, ranging from traditional lab-based setups to real-world scenarios (Figure 2). These studies have attempted to investigate interactions that are carried out face-to-face, in the physical presence of another person (but not face-to-face) and mediated by a machine. The tasks used in these studies include finger pointing and/or finger tracking exercises [61], music performance and economic exchange among others. While a majority or tasks explore collaboration and reciprocity, there are some studies such as the one detailed by Sinha et al. [50] where even competitive behaviour among participants is explored. We can see from this that a large portion of the investigations that use hyperscanning to study social interactions do so in a real-world setting. Here, by real-world we mean anything that does not involve an individual having to wear a specialised piece of equipment in order to enter an immersive VE. Given that there now appears to be a rising number of people interacting in immersive VEs, it is imperative that we explore the neural underpinning of these interactions in VEs. We believe that results from such studies can help tailor these environments to suit and even promote collaboration amongst individuals.

However, besides an exploratory study by Barde et al. [8] and a larger one by Gumilar et al. [25] (Figure 3), there appear to be no studies that have investigated social interactions in VEs using the hyperscanning technique. Results from both these studies demonstrate that inter-brain synchrony can be achieved in a manner similar to that demonstrated in real-world studies. However, the social interaction mechanisms that enable this are yet to be understood. With this in mind, the study laid out in this paper, seeks to begin the process of isolating and investigating each of the elements that make up the process of social interaction. Here we choose to explore the role that eye gaze plays in social interaction, and it's effects on inter-brain synchrony in a VE. Before we describe the study, we will briefly cover some literature related to the role eye gaze plays in social interactions.

2.2 Eye gaze

Eye gaze serves as an important cue in human communication [13, 24]. It forms an important constituent of face-to-face non-verbal communication [57]. The effects of eye gaze on inter-personal communication have been the subject of research for a long time [22, 28, 32, 57]. Eye gaze is capable of conveying turn taking, direct attention and interest in a conversation among other things [28, 57]. It has also been shown to have strong links with the display of emotions in human beings [3].

There are generally thought to be two forms of eye gaze: direct and averted [28, 32, 48]. These different eye gaze direction types have been shown to generate varying brain signatures [3].

Research has demonstrated that direct eye gaze is correlated with the activation of the prefrontal cortex area, while averted eye gaze is related to the activation of the parietal area [48]. The direction of eye gaze is also said to be an indicator of one's intentions. Tipper et al. [55] have demonstrated that one's internal motivation towards attending/approaching or avoiding social activity tends to be reflected in a manner in which eye gaze shifts. For example, the display of averted gaze during a conversation could be an indicator of a loss of interest in the conversation, or that the participant's attention has been momentarily captured something else [30]. The motivation that drives eye gaze can be divided into approach and avoidance Hietanen et al. [28]. Approach based motivation tends to result in direct eye gaze and emotions such as joy, love and anger are generally expressed more with direct gaze. Avoidance oriented emotions such as embarrassment and disgust tend to be expressed with averted gaze to a large extent [3].

These studies clearly demonstrate the importance of eye gaze in non-verbal face-to-face communication. By observing eye gaze, people can extract a meaning from a facial expression [31]. In fact, humans appeared to remember better a face that is coupled with direct eye gaze than the one with averted eye gaze [37]. However, conveying this in a VE is a significantly harder task. The use of avatars has been a feature in computer games and immersive virtual environments [57] such as Mozilla hubs and AltSpace VR. These environments allow multiple people to interact and collaborate in environments irrespective of the physical distance between them while being able to see virtual representations of themselves and each other. Unfortunately, even with the current state of technology that allows for gaze directions to be seen in real-time, we are unable to tell if the two interacting participants in a collaborative VE are 'in sync'. As with real-world hyperscanning studies that have explored the concept of mutual and joint attention and their effects on inter-brain synchrony [34], we must study how the direction of gaze in VEs impacts inter-brain synchrony among participants. The current body of work in the field demonstrates that there is a significant effect of sharing eye gaze in a collaborative VE [6, 7, 10, 52].

Given this body of evidence that points to the positive role of eye gaze in collaborative VEs, it is imperative that the neural correlates gaze in VEs are studied. As we have covered earlier in this section, eye gaze has been shown to be closely associated with emotion. There is also work in the field that demonstrates how neural activity is correlated to gaze [22, 44, 45]. Research has also demonstrated how specific areas of the brain are activated based on gaze [14, 28]. Despite this, to the best of our knowledge, there is no study that explores the effects of eye gaze on inter-brain synchrony between two participants in a collaborative VE. The next section briefly outlines the methodology that will be used to pursue this line of research.

2.3 Hypotheses

Inter-brain synchrony research has been studied in the real-world. Yet, there is only one study that explored the inter-brain synchrony inside VR, which was conducted by Gumilar et al. [25]. The study has shown that that VR and real-world demonstrated a similar result of inter-brain synchrony [25]. Given the limited number of studies and rise of collaborative virtual environments, it makes sense to study this in VR. Having laid down the results of previous studies, this current research will have the following hypotheses :

- The direct-eye-gaze condition would have more significantly different inter-brain synchrony than averted or natural-eye-gaze conditions.
- The averted-eye-gaze condition would result in a significantly different level of inter-brain synchrony in compared to natural eye-gaze-condition.

3 METHOD

3.1 Procedure

As stated in the earlier section, the goal of this study is to evaluate the role of eye gaze on inter-brain synchrony between two participants in a collaborative VE. In order to achieve this, we have designed a simple experiment that consists of a finger tracking task. We have chosen to implement the finger tracking task here similar types of tasks have been expensively used in hyperscanning research [15, 25, 61]. The major difference between the task that we will be implementing in this study and previous hyperscanning studies that employ this methodology is that the participants in our study will be required to keep looking at their respective avatars' eyes during the task.

Every participant will be required to track their collaborator's finger in the VE as closely as possible while looking into their eyes. Finger tracking has been widely used as a way to study human interaction with VR [18, 29, 49]. Yun et al. [61] has specifically utilized the finger tracking in their experiment to investigate the inter-brain synchrony. It is being used here in conjunction with gaze to explore if there is an effect of gaze on the inter-brain synchrony during the finger tracking activity. The finger tracking will be carried out across three conditions, namely; direct gaze, averted gaze and natural gaze (Figures 4a - 4c). In the direct and averted gaze conditions, the eyes of avatars will be fixed at a pre-determined position, while the in the natural gaze condition participants' eye gaze will be reflected in real-time using eye trackers present in the Vive Pro Eye headsets that will be used for the study.

Since this is the first attempt to investigate the impacts of different eye gaze directions on inter-brain synchrony in VR, we would like to minimize some other factors that can influence the result. Therefore, we do not take a full body of avatar and we use only the upper part of the body, specifically head where the eyes sit. For our future experiment, we would like to explore how various types of avatar appearance affect the brain synchronization of people while taking into account the eye gaze directions. We will carry out a between-subjects study in order to minimise any effects of learning and familiarity between participants. Additionally, we will recruit participant pairs who do not know each other and will endeavour to keep participants from seeing each other in the real-world in order to obtain the best possible results.

This study is going to collect various types of data, which includes, firstly, behavioral data (i.e., subjective user experience toward his or her partner), and, secondly, physiological data (including eye and brain data such as pupil diameter, gaze direction, opened eye, closed eye, and brain signals). All behavioral, eye, and neural

(a) Averted eyes **(b) Directed eyes** **(c) Natural eyes**

Figure 4: Eye gaze conditions

data recorded during the experiment will be analysed offline to determine the correlation between eye gaze and inter-brain synchrony during a collaborative activity in a VE.

Considering the design of this study, it would provide several benefits. Firstly, it can inform us that VR can elicit inter-brain synchrony among its users. Secondly, it would provide a better information on a specific parameter, i.e. eye gaze direction, that initiates such inter-brain synchrony. Having revealed such data, one can apply eye gaze direction as an indicator to gauge an effectiveness of remote collaboration in VR.

3.2 Participants

We aim to recruit 30 pairs (60 participants) for this study. Care will be taken to ensure that participants do not know each other. All participants will need to be at least eighteen years old to participate, have no known health concerns and be able to provide consent without any help.

3.3 Apparatus and Virtual Environment

We will make use of the following hardware and software components in order to run the study:

(1) Head Mounted Display (HMD): We will use two Vive Pro Eye HMDs equipped with eye trackers. Eye tracking data will only be used in the "natural" gaze condition during the experiment.
(2) OpenBCI EEG Electrode Cap Kit: Two OpenBCI EEG Electrode Cap kits [3] will be used to record neural activity of the two participants. Each of the kits contains a 16 electrode EEG gel cap that will be connected to a 16 channel biosensing board (Cyton+Daisy) [4].
(3) Software: The study uses different software tools to create the VE in which the experiment is run, capture the data and process it. the VR environment was designed and built using Unity 3D[5]. For the study, the entire experiment is initialised and run within this environment. Signals from the biosensing board are streamed via a Bluetooth connection to the Unity programme running on a laptop. The eye tracking and EEG data are synchronised using the LSL (Lab Streaming Layer) for Unity plugin. LSL is a system that affords the unified collection of time series data in a synchronised manner [35]. Integrating the LSL for Unity plugin into our build allows us to synchronise the collection and collation of eye tracking and EEG data into a single CSV file that can be processed offline.
Given that this experiment involves the interaction of two remote individuals in a virtual environment, there was need to network the two PCs being used for this study. Networking between the two systems was achieved using the Photon Unity Network (PUN2) package. In addition to this all the data that is collected during this study will be processed using tools available for both MATLAB and Python. Figure 5 shows the signal flow between the all the hardware and software components used in the study.
(4) Questionnaire : A standardized questionnaire in measuring social presence in VE will be utilized in this experiment [58]. Participants will provide their responses before and after the experiment.

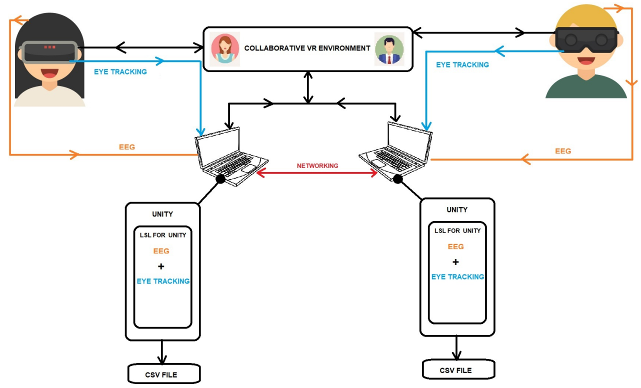

Figure 5: Signal Flow

4 CONCLUSION

This paper has laid out the direction for a study that will explore the role of eye gaze in inter-brain synchrony among participants in a collaborative VE. We have covered literature that has motivated the work that we propose to carry out in the area. We expect the study described in this paper to make important contributions to fields of Human-Computer Interaction (HCI) and social neuroscience. Being able to understand how non-verbal communication cues can affect the quality of interactions in VEs can help us design VEs that promote inter-brain synchrony among individuals collaborating in such environments. With this study, we can determine whether inter-brain synchrony can be achieved in VR. We can also identify the specific parameters that can initiate and encourage inter-brain synchrony.

Having revealed the inter-brain synchrony, it can gauge and enhance a process of collaboration for the HCI community and Computer-Supported Cooperative Work (CSCW). For example, as two or more people, who are separated geographically, collaborate in VR to solve a problem, e.g. fixing a broken cable, they have no idea precisely what happens with each other. A person may not know that their partner does not correctly understand which

[3]https://shop.openbci.com/collections/frontpage/products/openbci-eeg-electrocap
[4]https://shop.openbci.com/collections/frontpage/products/cyton-daisy-biosensing-boards-16-channel?variant=38959256526
[5]https://unity.com/

line is currently being explained. A person does not know accurately whether their partner fully engages in a conversation or a process of solving a broken wire. By measuring the inter-brain synchrony, it can serve as an indicator of how people work together. The inter-brain synchrony can hold various information on engagement, understanding, cognitive load, which significantly determine collaborative work. It can eventually be used as an implicit measure of collaboration quality as well as to adapt the environment to increase brain synchronization. Thus, measuring the inter-brain synchrony can aid and enhance a process of remote collaboration in VR and CSCW in general.

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