Inter-brain Synchrony and Eye Gaze Direction During Collaboration in VR

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ABSTRACT

Brain activity sometimes synchronises when people collaborate together on real world tasks. Understanding this process could to lead to improvements in face to face and remote collaboration. In this paper we report on an experiment exploring the relationship between eye gaze and inter-brain synchrony in Virtual Reality (VR). The experiment recruited pairs who were asked to perform finger-tracking exercises in VR with three different gaze conditions: averted, direct, and natural, while their brain activity was recorded. We found that gaze direction has a significant effect on inter-brain synchrony during collaboration for this task in VR. This shows that representing natural gaze could influence inter-brain synchrony in VR, which may have implications for avatar design for social VR. We discuss implications of our research and possible directions for future work.

CCS CONCEPTS

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

KEYWORDS

Hyperscanning, Eye gaze, Remote collaboration, Brain synchronization, Inter-brain synchrony, Virtual Reality (VR), Brain, Social neuroscience, Computer supported cooperative work (CSCW)

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1 INTRODUCTION

This paper reports on a study of the impact of eye-gaze behaviour in Virtual Reality (VR) on inter-brain synchronisation. In recent years researchers have begun to explore more of the social neuroscience underpinnings of face to face collaboration. In particular, monitoring brain activity using electroencephalograph (EEG) or other devices has found that inter-brain synchrony can sometimes occur between people collaborating on the same task [27, 34]. This is where the electrical signals of different EEG electrodes become in phase, and can be detected using a technique known as hyperscanning [7, 9]. In this case, people report being 'in sync' or 'connected' with each other, and can produce better collaborative outcomes.

Brain synchronisation is not well understood, partly because of the difficulty in controlling some of the factors that might cause it. For example, does being aware of a person's gaze or facial expression help with brain synchronisation? VR provides one environment where controlled experiments can be conducted because virtual avatar representation can be easily controlled. Thus, in our work we are interested in exploring brain synchronisation in VR. This could help to better understand why it occurs in real world activity. A second motivation is that it could inform the design of virtual avatars that could increase the occurrence of brain synchronisation, and so provide a better collaborative experience.

In this paper we detail an experiment where we gauge the effects of eye-gaze in VR on neural connectivity using a hyperscanning technique. We first review related work, highlighting the novelty of our research. Next we describe our system setup and experimental method. This is followed a presentation of the results, and discussion. Then ending with a conclusion and directions for future work.

2 RELATED WORK

Eye gaze, as other researchers have demonstrated, significantly affects the quality of interpersonal interactions in both the real world [26] and VR [12]. Given that eye gaze forms an integral part of interpersonal interactions, it is important that its function in collaborative VR is studied.

Several studies have demonstrated that the direction of eye gaze i.e., averted or direct, is capable of eliciting a range of different physiological responses, such as increased brain activity, heart rate, and skin conductance [5, 17, 21, 28]. For example, people who perceived that their gaze was being averted by an observer demonstrated increased brain activity in the occipital lobe, which is mainly responsible for processing visual information [15]. This activation infers a shifting in spatial attention that is directed by the averted gaze [15], which has a distinct brain network from a direct gaze [6]. In the case of direct gaze, its perception has shown to activate areas in the brain related to self-awareness [17, 24], attention [18], and social interaction [5]. In a virtual interaction, it has shown to elicit a positive affect [18], which may contribute to a sense of being given a “signal” of attention by another person [24].

However, the neural underpinnings of eye gaze in social interactions and its affect on inter-brain synchrony have not been extensively researched. While some work exists in this domain [24, 25, 31, 40], this centres primarily around the use of functional Magnetic Resonance Imaging (fMRI) [31, 36, 40] and there is no study to date that explored eye-gaze and its effect on inter-brain synchrony during a collaborative scenario in VR.

Different eye gaze directions convey different information [6]. They also reply on different neural processing pathways [17, 23]. In comparison to averted eye gaze, direct gaze captures and holds attention [10, 33]. It is an indicator of interest during communication [13, 31]. The natural eye condition represents normal eye gaze behaviour. Natural gaze conveys information about signaling behaviour as individuals interact in a certain context such as taking a bite as one eats together with another person [38]. Depending on a relationship, it can trigger a different type of gaze direction during a communication [38]. Given that different eye gaze types have shown to have varying impact on interpersonal interactions from neurological and psychological perspectives, this study aims to investigate their impact on inter-brain synchrony. Therefore, we have chosen to implement two explicit gaze conditions (direct and averted) along with the natural gaze condition. The pre/post training sessions have been carried out to see if there's any difference in inter-brain synchrony before and after the representative social interaction (training session) has been carried out. This procedure has been adapted from from a previous study [41].

This paper reports on a study conducted to gauge the effects of eye gaze on inter-brain synchrony between interacting individuals in VR. We do this using a hyperscanning technique, which is a method used to simultaneously measure the neural activity of two or more people [2, 8, 29]. The time series data acquired via this method can then be compared over the entire duration of the study, specific portions of the study or at discrete positions on the timeline to determine if the individuals in the study demonstrate inter-brain synchrony or not [8, 9].

While hyperscanning has been used for nearly two decades, the last decade has seen an exponential rise in its use owing to easier access to high quality equipment to monitor neural activity. Real-world studies using the technique have empirically demonstrated the existence of inter-brain synchrony among participants playing a card game [3] and flying an aircraft [32, 35] among other activities. These studies have demonstrated that connectedness between individuals can be measured at the neural level. However, with the increasing proliferation of VR based inter-personal interactions, the phenomenon of inter-brain synchrony and the effects physiological cues both implicit and explicit have on it must be studied. The remainder of this paper describes the methods that were used to conduct such a study, the results obtained and their implications for the design and development of collaborative VR in the future.

3 METHOD

3.1 Participants

Thirty participants (20 males, 10 females) between 20 and 66 years old (M=31.6, SD=8.7) were recruited for the study. More than half of the participants (n=23) had experienced VR at least once before taking part in the experiment. None of the participants reported any physical or neurological issues that precluded them from participating in the experiment. The study was approved by the Human Participants Ethics Committee of the host institute. All participants provided informed consent prior to taking part in the experiment. All participants were given a $20 gift voucher as compensation for taking part in the study.

3.2 Design

We developed a VR system that enabled two people to perform a finger tracking task using the VR controllers. Participants were able to see and interact with each other's avatars in VR. Both the avatars exhibited a fixed set of eye gaze behaviours. Eye gaze in VR was captured using an eye-tracker integrated in the VR head mounted display (HMD), and consisted of three different gaze conditions (see Figure 2):

(1) **Averted gaze**. For this eye gaze condition, we turned off the eye tracker and fixed the avatar gaze so that each participant perceived that his or her partner was always looking away from them (towards the left).
(2) **Direct gaze**. Similarly, for this condition we turned off the eye tracker of the VR HMD and fixed the avatars' eye gaze to be directed straight at each other.
(3) **Natural gaze**. In this condition, we turned on the eye tracker so that the avatars' eyes followed the natural movement of the participants' eyes.

For the experiment both participants were asked to look at the eyes of each other's avatars while performing a finger-pointing and finger-tracking exercise. Finger pointing refers to a condition in which both participants had performed to point the index finger to each other inside VR by using a controller (Figure 1(a)). Finger tracking refers to the “training” portion of the study in which both participants moved their finger to the same direction (either left or right). The avatar was adopted from the sample figure that is available in Tobii XR SDK. The finger-tracking exercise involved participants playing the roles of leader and follower alternately. The leader was tasked with moving their finger in an arbitrary pattern in a manner such that it was slow enough to follow. This exercise has previously been shown to result in brain synchronisation in the real world [41] and in VR [16]. The brain activities of the participants were recorded via an EEG cap that the participant wore throughout the experiment for both the finger-pointing and finger-tracking exercise (Figure 2(a)).

Finger pointing and tracking were achieved in VR by the participants holding VR controllers in their hands. As they moved their hands around, their virtual avatar mimicked the real hand motion (see Figure 1(a)). The head of the avatar followed the orientation of the VR headset. A model of a hand was used to provide participants with a sense of embodiment in VR. Since this study focused on eye gaze, each person was only represented in the form of a virtual head and hands (Figure 1(b)). The entire VR environment was designed and built using Unity.

We made use of the following hardware and software in order to run the study:

(1) **VR Head Mounted Display (HMD)**: We used two HTC Vive Pro Eye [1] HMDs equipped with eye trackers.
(2) **OpenBCI EEG** Electrode Cap Kit: Two OpenBCI EEG Electrode Cap kits [2] were used to record neural activity of the two participants. Each of the kits contains a 16 electrode EEG gel cap that was connected to a 16 channel biosensing board (Cyton+Daisy) [3].

3.3 Procedure

We modelled our experiment procedure on an existing experimental paradigm [41] for a real world finger tracking task, which has been reproduced previously in VR [16]. We used a within-subjects design where each of the pairs of participants experienced all of the three gaze conditions, i.e., averted, direct, and natural, in a counter-balanced order.

Each of the eye gaze direction conditions followed a simple three steps process which involved (1) a pre-training finger pointing exercise, (2) a training or finger tracking exercise considered a form of social interaction [41] and (3) a post-training finger pointing exercise. All of these sessions for each of the gaze conditions were initiated by verbal commands given by the experimenter. Each of the verbal commands was also logged using a marker in the recording software for both Unity and BrainFlow (a software to acquire EEG data from OpenBCI cap). All of the sessions mentioned here were run once each for every hand per participant. Throughout the finger pointing and tracking, pairs were asked to look at each other i.e. maintain eye contact with their partner's avatar.

3.3.1 Session 1 – Pre-Training. For this session, participants were required to perform a simple finger pointing exercise. This session was split into two parts – one for each arm of the two participants. Prior to starting this session, participants were asked to sit facing each other and stretch one of their arms out with the index finger pointing out. Each participant raised the opposite arm so as to form a mirror image (see Figure 1(a)). In other words, if participant 1 raised the right arm, then participant 2 raised the left arm. Each finger pointing trial lasted for a minute.

3.3.2 Session 2 – Training. In the training session, participants were asked to perform a simple finger tracking exercise as a form of social interaction [41]. This involved following the finger tip of the other person, as closely as possible (see Figure 1(a)). This was repeated with both arms. The arm to be used for each part of this session was verbally communicated to the participants by the researcher. Finger tracking lasted one minute for each hand. The rationale behind carrying out this exercise was to mimic some form of social interaction based on the premise that social interaction promotes the onset of inter-brain synchrony [41].

3.3.3 Session 3 – Post-Training. The post-training task was the same task performed in the session 1 (pre-training) session of the study. The entire experiment took about 40-50 minutes.

3.4 Data Analysis

The current experiment has used the MNE-Python package [14] and the HyPyP package for pre-processing the raw EEG data. As suggested by Burgess [4], the Circular Correlation Coefficient (CCorr) is less susceptible to recognizing spurious inter-brain connections. Thus, the current experiment has utilized CCorr [20] in order to measure synchronicity of the two brain signals. The formula has been embedded into the HyPyP module [1], which is primarily designed for analyzing inter-brain synchronization data.

For each pair, there were 256 CCorr scores which indicate the magnitude of inter-brain synchrony for all possible pairs (16 electrodes x 16 electrodes = 256 electrode pairs). By applying a cut-off (p <.05) to a distribution of the CCorr scores (256 CCorr scores for each pair), we then extracted only the CCorr scores that were above the threshold. Those pairs with CCorr scores that did not fall within the 95% confidence interval were retained as significant CCorr scores.

The total number of aligned electrode pairs (significant connections) were counted for each eye gaze condition within a specific frequency band, i.e., theta, alpha, beta, and gamma. Additionally, a two-way repeated measures ANOVA was run to ensure that there was a statistically significant difference between the pre and post training conditions for this set of electrodes. This analysis was performed using JASP [22].

The calculation of CCorr score have been facilitated by the HyPyP library [1]. To the best of our knowledge, this is the most comprehensive python library that is available to measure inter-brain synchrony. Hypyp works on top of MNE-Python [14].

4 RESULTS

A two-way repeated measures ANOVA, was conducted to compare the main effects of eye gaze direction and social interaction (reflected in finger-tracking task) as Independent Variables (IVs), as well as their interaction effects on the number of inter-brain connections, Dependent Variable (DV). Eye gaze has three levels (averted, direct, and natural). We compared inter-brain synchrony

[1] https://www.vive.com/nz/product/vive-pro-eye/overview/
[2] https://shop.openbci.com/collections/frontpage/products/openbci-eeg-electrocap
[3] https://shop.openbci.com/collections/frontpage/products/cyton-daisy-biosensing-boards-16-channel?variant=38959256526

(a) A pair interaction with VR

(b) Appearance inside VR

Figure 1: An interaction of pair during experiment with VR and how the pair saw each other inside VR

(a) Averted eye

(b) Direct eye

(c) Natural eye

Figure 2: Three different eye gaze directions under which all participants have performed finger-pointing and tracking exercise (training)

before and after training (finger-tracking) across the three eye gaze conditions. For both pre and post-training, the pairs performed a finger-pointing task (see Figure 1). In between the tasks, the pairs performed the finger-tracking activity, which is considered a form of interaction [41].

Eye gaze and social interaction did not produce significant effects in all frequency bands. However, the result did yield an interaction effect between the two IVs with an effect size of 0.120, indicating that 12 % of the variance in the number of inter-brain connections was explained by the interaction between eye gaze and social interaction (finger tracking), $F(2,14) = 9.79$, $p < .001$. This indicates that there was a combined effect for eye gaze and social interaction (finger tracking) on the number of inter-brain connections in alpha frequency (see Figure 3). For detailed connections, please refer to Figure 4.

Given the existence of an interaction effect between eye gaze and social interaction, a post-hoc analysis was run; t-test with Bonferroni correction. This revealed a significant difference between pre-training ($M = 14.06$, $SD = 2.28$) and post-training, ($M = 11.06$, $SD = 4.86$) for the natural eye gaze condition in alpha frequency.

4.1 Correlation between the percentage of gaze overlap and inter-brain connections

The system outputs raw data in the form of Cartesian coordinates. For the purposes of our analysis, we converted this to degrees in order to calculate the angle of eye movement of each participant. The Field of View (FoV) that encompasses binocular vision spans approximately 120° [37]. This is made up of two monocular fields

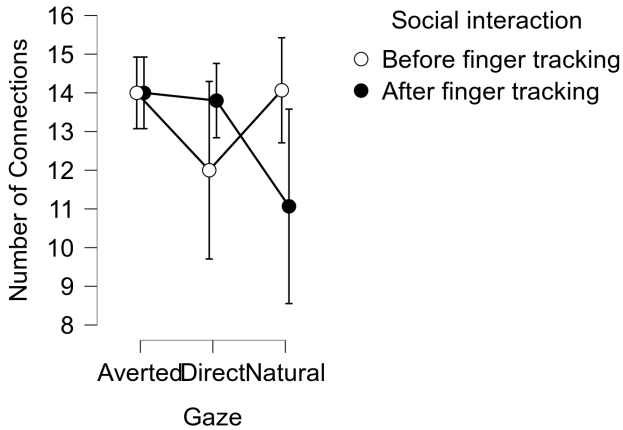

Figure 3: Number of inter-brain connections for all gaze directions, i.e., averted, direct, and natural, in alpha frequency

of view, which are 30° each. A classic study related to FoV [30] has indicated that humans are able to recognize symbols or objects in a range of 60° (30° right and left). The current analysis considers a 30° view frustum for each of the participants. This 30° view frustum accounts for both the horizontal (15° either side of the median plane) and vertical (15° above and 15° below the horizontal plane passing through the eyes) viewing directions. If an overlap between these frustums occurs, then the participants are considered to be looking at each other. In addition to meeting the condition of overlapping view frustums, we also set a minimum gaze fixation threshold over which the overlap must occur. This was set to 100ms based on literature that demonstrates that this is the minimum period required for humans to extract meaningful information [19] during gaze fixation. The percentage of overlap in each of the gaze conditions is shown in Table 1. This indicates the extent to which the participants looked at each other during the course of a given task. Such criteria have been applied for all eye conditions.

We also studied the correlation between the percentage of overlap and the number of inter-brain connections. We then applied Pearson correlation between these numbers for every eye gaze condition for both pre and post-training sessions.

4.1.1 Averted gaze in post-training (averted-post). The only significant correlation occurred in the averted eye gaze condition for the post-training phase. The correlation was been found in all frequency bands, i.e., theta, alpha, beta, and gamma (see Table 2). The lowest correlation was found in theta (0.52). The highest correlation was observed in alpha band (0.62), followed by the beta band (0.61) and gamma band (0.56). The average correlation across the four frequencies was 0.57 (57%).

5 DISCUSSION

Our results show that gaze direction has a significant impact on inter-brain synchrony during collaboration in VR. The impact appears especially obvious in terms of the number of inter-brain connections between pre and post-training in natural gaze condition in the alpha frequency. The alpha band is known for attention suppression [11]. The finding suggests that the interaction during natural gaze may have given people a better sense of focus in order to suppress inputs from other modalities [11]. The current result support and extend the scope earlier results by changing the focus of participants from fingertip to virtual eyes of the avatars. It also suggests that the finger pointing and tracking task across both studies may share the same underlying neural mechanism. The effect of natural gaze on inter-brain synchrony appears to be apparent when combined with some form of a social interaction task.

There was a positive correlation between the percentage of gaze overlap and the number of inter-brain connections in the averted gaze condition for the post-training phase. This may have been facilitated by a similar amount of effort that each person put in to attract the other person's attention. Averted gaze has caused shifting of joint-attention [13]. When the pairs had a longer averted gaze, their attention may have been oriented into the same space (joint attention), indicated by the gaze overlap in averted post-training being higher than the one in pre-training. This may promote the correlation between the number of inter-brain connections and the percentage of gaze overlap in averted post-training condition. Another plausible explanation is that a previous experiment indicated that visual awareness can aid joint attention [39]. Despite the show of averted gaze, the pairs were fully aware that they had been instructed to look at each other throughout the experiment no matter how the other person's avatar appeared in VR.

5.1 Limitations of the study

There are several major limitations that affect the extent to which the results can be generalised:

(1) Avatar: The avatar used for this study is not fully representative of a human being. Appearance of an avatar may have affected how the other person feels and perceives it, which may impact the inter-brain synchrony.
(2) Participants were asked to look at each other and not asked about their feelings (subjective ratings) of immersiveness of the environment and the connection they felt with their partners. The study only relied on objective measurement (brain signal that was acquired through EEG) but not a subjective measurement (self-report via questionnaire).

5.2 Study Implications

The current research has several implications. Firstly, monitoring inter-brain synchrony during remote collaboration in VR should take into account the gaze behaviour of the people involved. Secondly, when creating a system that is used for monitoring inter-brain synchrony during a collaboration in VR, one should take into account that gaze fixation times of 100ms or more indication that participants are paying attention. Finally, the results imply that if designers want to develop social VR experiences that enable brain synchrony, they should support natural gaze behaviour in the user's virtual avatars.

Furthermore, revealing the inter-brain synchrony can have an implication for monitoring a process of collaboration in VR. For example, if an instructor attempts to explain about a certain material to a student, by monitoring the inter-brain synchrony, we would be able to detect at which point and method that can enhance or

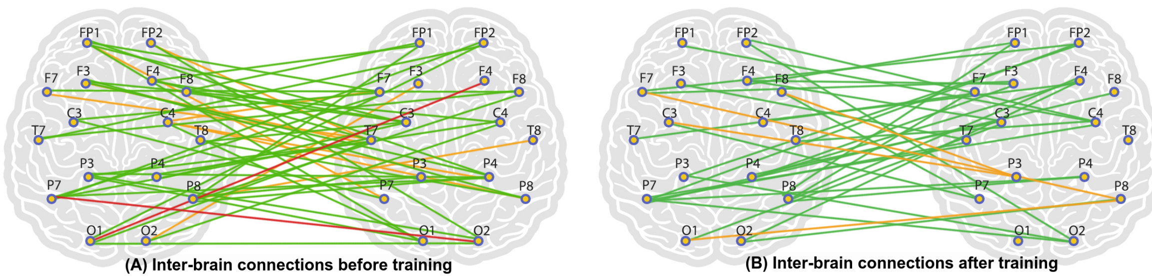

Figure 4: Inter-brain connections in natural gaze condition before training (finger-tracking)(A) and after training (B) in alpha frequency

%	Averted-Pre	Averted-Post	Direct-Pre	Direct-Post	Natural-Pre	Natural-Post
Looking (%)	51.52 %	64.11 %	65.76 %	74.51 %	81.50 %	81.07 %
Not looking (%)	48.48 %	35.89 %	34.24 %	25.49 %	18.50 %	18.93 %

Table 1: The proportion of gaze overlap (looking) and non-overlap (not looking) for all eye conditions (averted, direct, and natural) in pre and post-training

Band	r	*p*
Theta	0.52	0.04
Alpha	0.62	0.01
Beta	0.61	0.01
Gamma	0.56	0.02

Table 2: Correlation between percentage of gaze overlap and the number of inter-brain connections (averted post-training)

decrease the inter-brain synchrony between the instructor and student. Having said that, revealing small communicational cues that can affect the inter-brain synchrony in VR can help us to enhance collaborative tasks in VR. Such a system could be useful in a remote training task. For example, a trainer with access to one's full VR driving simulation can help to monitor to what extent the effectiveness of communication between trainer and trainee during the driving simulation.

6 CONCLUSION

This paper investigated the effect of eye gaze on inter-brain synchrony in a social interaction task in VR. We observed a significant difference between inter-brain connections in the pre-training phase versus the post-training phase in the natural eye gaze condition. We also observed a significant correlation between the percentage of gaze overlap and the number of inter-brain connections in post-training phase in the averted gaze condition. These two findings demonstrate that eye gaze has a significant effect on inter-brain synchrony and as a result, the quality of the interactions.

In the future we would like to explore the role eye gaze plays in inter-brain synchrony in VR by using more realistic interactions. The addition of visual distractors could provide us with information on how VEs could be designed so as to encourage and improve inter-brain synchrony by actively engaging eye contact. However, this has to be tempered with the understanding that our study demonstrates that inter-brain synchrony increased in the natural eye gaze condition. Additional studies should be conducted to explore a range of different real-world tasks such as collaborative design, or building etc. It will also be important to study how gaze fixation times contribute to inter-brain synchrony. We believe such exploration will help advance our understanding of the role gaze plays in collaborative VR, and build the framework for systems that can initiate, promote and maintain high levels of inter-brain synchrony in order to enable better interpersonal interactions in VR.

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