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Interpersonal EEG Synchrony while listening to a story recorded using consumer-grade EEG devices

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Abstract. Interpersonal EEG synchrony derived from the hyperscanning technique has the potential to reveal brain mechanisms beyond the border of traditional analysis within an individual subject. However, the inter-brain connectivity has not been fully investigated using wearable consumer-grade EEG devices which can enable a variety of application in a real-world scenario. In this study, we investigate interpersonal synchrony by capturing EEG signals using wearable EEG devices, from multiple participants (N = 6, 7, 15) who simultaneously listened to a novel being read to them. The results show that similar power-spectral patterns from neural responses evoked by perceiving the same auditory stimuli exhibit the synchrony, which is likely to have a transient characteristic rather than being stationary.

Keywords: Inter-brain synchrony · Electroencephalogram · Hyperscanning

1 Introduction

Hyperscanning, a neuroimaging technique that simultaneously measures the brain activity from multiple subjects, has demonstrated its usefulness in neuroscience studies beyond the analysis within an individual brain [1]. Inter-brain correlation of electroencephalography (EEG) has been recently proposed a marker of attention, engagement, and emotion [2]. Despite its potential, such brain correlates were mainly discovered in laboratory settings, where the reproducibility of EEG synchrony in real-world scenarios has yet to be fully explored. Further, most of the previous studies in neurophysiological synchrony were conducted using sophisticated high-cost EEG devices, therefore, limiting the number of participants. The recent development of wearable EEG enables a possibility to explore inter-brain synchrony among a higher number of individuals using portable wireless EEG in naturalistic environments. Here, we investigate the synchrony of EEG signals recorded from multiple participants who simultaneously listened to a reading-out-loud sound of a novel story in a group setting with minimal control, primarily aiming to monitor synchrony between the emotional experiences of the listeners.

2 Methodology

2.1 Data Collection

Data was collected in three different sessions from the informed participants who attended a science exhibition and volunteered to involve in this study (Figure 1). Brainwaves were simultaneously recorded at the sampling frequency of 220 Hz from 4 electrodes (TP9, Fp1, Fp2, and TP10) of Muse-2014 wearable EEG headbands*. After putting on the EEG headband and ensuring the position and impedance appropriateness, the main experimenter started to read out loud the first two chapters of a novel written by Arnon Grunberg at a naturalistic speed. Participants were encouraged to minimize body movements to avoid artifacts. The story lasted for 28.13 minutes on average across three sessions. Upon data quality inspection and discarding data of participants who left the experiment before it ended, the numbers of remaining participants for each session are 14, 6, and 7.

Fig. 1. Experiment set-up

2.2 Data preprocessing

Data were trimmed at the arbitrarily selected starting and ending points. The data compression module of MUSE inevitably led to the jitters in the EEG timestamps, which is crucial information to temporally align EEG signals from all participants. To alleviate the issue, a linear regression technique together with a sliding window technique was exploited in order to reduce the deviation of the timestamps. In particular, timestamps within one sliding window were fitted to a linear curve and the corrected timestamps were acquired from this linear model; in addition, overlapping technique was also em-

* More specification can be found in `http://developer.choosemuse.com/`

ployed to mitigate a sharp increment or decrement of timestamps at the end of the window. The corrected timestamps were yielded by taking the average of overlapped windows. Afterwards, EEG data were re-sampled at new equal-bin timestamps of 200 Hz, which was applied to all participants in the same session, using an interpolation technique. Finally, signals of interesting have a duration of 24.09 minutes (3.04 minutes from the start and 1.03 minutes before the end of the task).

Subsequently, a Butterworth band-pass filter were applied to acquire signal within the frequency of interest between 1 and 40 Hz. To tackle adverse effects of artifacts, an artifact removal technique based on Independent Component Analysis (ICA), implemented in EEGLAB [3] was employed. Specifically, ICs were computed using *infomax* algorithm and then visually evaluated. The artifactual ICs were then removed from the source space, and the remained ICs were used to project back to original space to generate artifact-free EEG data. Normalization by subtracting mean values was then applied to obtain zero-mean EEG signals.

2.3 Synchrony measurement

The EEG synchrony of each dyad in the same session was assessed by computing the correlation of sliding power spectra. Specifically, power spectral density (PSD) was computed from each EEG channel in each particular window whose size was 5 seconds (20% overlapping). In this study, a multi-taper PSD technique implemented in Chronux toolbox[4] was used to obtain PSD; the taper bandwidth was set to 2 Hz in each 1-second sliding window, and the number of tapers was set to 16. Afterwards, spectral power levels within particular frequency bands were averaged to yield power band of theta (4-8 Hz), alpha (8-12 Hz), beta (12-20 Hz), and gamma (20-30 Hz).

Upon acquiring PSD series, the synchrony of EEG between participants *x* and *y* in the same session was measured by computing the correlation (r_{xy}) of PSD in a specific band and a particular channel using the following formula:

$$r_{xy}=\frac{\sum_{i=1}^{k}\left(PSD_i^x\text{-}\overline{PSD^x}\right)\left(PSD_i^y\text{-}\overline{PSD^y}\right)}{\sqrt{\sum_{i=1}^{k}\left(PSD_i^x\text{-}\overline{PSD^x}\right)^2\sum_{i=1}^{k}\left(PSD_i^y\text{-}\overline{PSD^y}\right)^2}} \tag{1}$$

where PSD_i^x represents PSD of a signal from subject *x* at the *i*-th window from all of the *k* windows, and $\overline{PSD^x}$ represents its average taken from all windows. As it is reasonable to assume that a pair of participants might not have a synchrony of PSD throughout the entire experiment but rather have intermittent synchronization due to fluctuating mental states, *k* is defined as the sliding window size for calculating correlation in the region of interest rather than using all data from the whole experiment. In this study, *k* is arbitrarily set as 20 and there is overlapping between consecutive windows; given the defined step size of PSD sliding window as 1 second, this means we are interested in finding a series of correlation of power spectra within a 20-second time-frame.

2.4 Statistical Testing

To test the null hypothesis that the power spectra time series of two different participants in the same session are not correlated, the non-parametric surrogate data method proposed in [5] was exploited. This approach randomizes PSD windows differently to build surrogate PSD time series and computes surrogate correlation. This process is repeated for 1,000 times to produce distributions in which the null hypothesis holds i.e., the chance-level of cross-participant PSD correlation. The original, non-permuted data are then compared to the surrogate distribution to obtain *p*-values which, in this study, were later compared with a significance threshold of 0.05.

3 Results

3.1 Transient correlation

The correlation coefficients of power-spectra time series from each pair of participants were averaged within the experimental session, separately by channel-frequency band. Then the values were aggregated from all pairs of participants to derive the grand-average, the 25th and 75th percentiles, the minimum and the maximum (Figure 2a,b,c). In addition, the coefficient at a particular window from a pair of participants, whose value is over 0.75 and its original PSDs significantly correlate, is also shown. In general, the averaged correlation coefficients are relatively low (between around 0.2 and 0.3) compared to an intermittent coefficient from a window. The results suggest that the synchronization of EEG power spectra is transient rather than stationary throughout the whole experiment. It is also noticeable that the correlations in theta and alpha are relatively higher than in beta and gamma, which could be owing to that the listening task might homogenously enhance the level of concentration and relaxation of participants [6].

3.2 Decline of correlation by the increased size of sliding window

It is sensible to assume that the size *k* of the sliding window for calculating correlation may affect the obtained results as it refers to the minimum duration of synchronous PSD. Henceforth, another investigation was conducted by varying the size of *k* from 10 to 100 seconds with an increment of 5 seconds. The results, depicted in Figure 2(d), suggest that correlation coefficients decrease when increasing the size of the sliding window. From this it can be deduced that the synchronization might not last long and the enlarged window might encompass the epochs where EEG signals are not synchronized. However, this phenomenon should be investigated further in a follow-up study. Moreover, one should investigate the possible increase of false-positive rates for small window sizes.

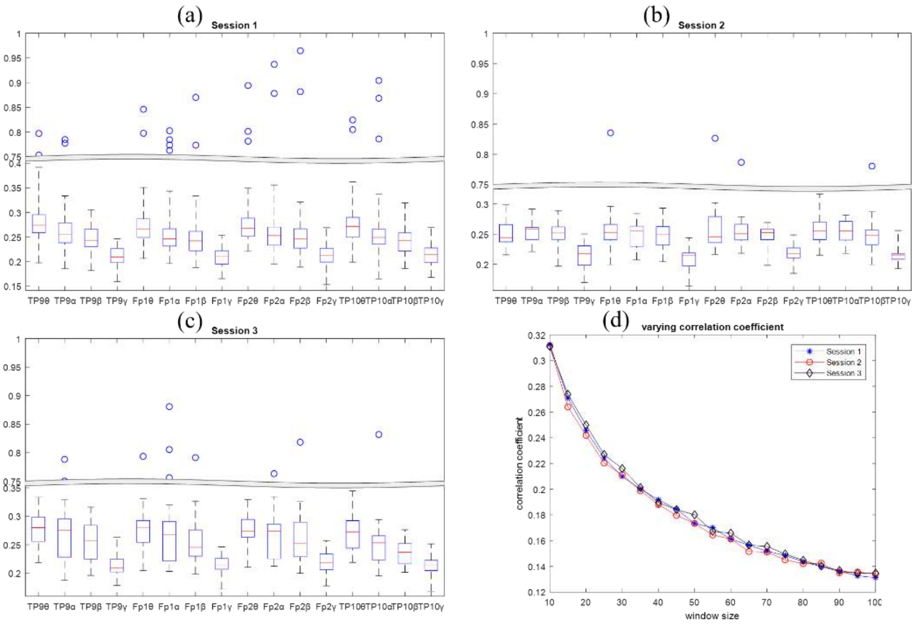

Fig. 2. The resulted correlation coefficient of power spectra averaged across all pairs of participants in the same session (session 1, 2, and 3). A correlation coefficient that is derived from significantly correlated PSDs at a particular window is shown as a circle. The decline of coefficients by increasing the size of the sliding window is displayed in sub-figure (d).

4 Discussion

This paper presents an investigation of synchrony in EEG data recorded in real-world environment with consumer electronics. Although EEG synchronization was discovered, the underlying mechanisms are yet to be revealed. The detected PSD couplings are mainly lying in low-frequency bands which are related to various brain activities such as attention, concentration, relaxation, and drowsiness [4]. Since the participants in this study did not provide any feedback, it is hard to relate the source of synchrony and relation with subjective mental state. Futures studies are encouraged to elaborate the mechanism of inter-brain synchronization by carefully designing an experiment that excludes potentially irrelevant cortical activity and social interaction [7] that might hinder the analysis and fully focus on a specific plausible cause of synchrony, for instance, shared attention, emotion, and stimulus perception.

In addition, we should note that the synchrony was computed by only using a frequency-domain approach, where the information in time domain was omitted. Therefore, the size and overlap of sliding window play an important role and might cause high variance. Our future work will include applying time-frequency approach, such as wavelet analysis, of inter-brain synchrony to gain further insights and employing statistical analysis to validate the detected synchrony. Further, the synchrony measurement should go beyond dyadic analysis and toward discovering a similar pattern among a group of multiple brains [8].

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