EAR-EEG FOR DETECTING INTER-BRAIN SYNCHRONISATION IN CONTINUOUS COOPERATIVE MULTI-PERSON SCENARIOS

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ABSTRACT

The hyperscanning method simultaneously acquires and relates cerebral data from two participants while performing cooperative activities. The aim of this work is to evaluate the performance of our novel EEG recording concept, termed ear-EEG, against on-scalp EEG as an alternative, user-friendly data acquisition approach for hyperscanning, in the task of identifying the most robust, EEG subbands for inter-individual neuronal synchrony detection in cooperative multi-player gaming. This is achieved through the estimation of neuronal synchrony produced by a highly localised time-frequency data association measure, termed intrinsic synchrosqueezing coherence (ISC). It is shown that for both the recording modalities the lower theta band is the most robust neuronal marker for inter-brain synchronisation during our own cooperative game called Bar Balancing. This is because the lower theta band yields: (i) highest correlation in neuronal synchrony between the modalities; and (ii) enhanced discrimination ability of significant neuronal synchrony detected in the easy and hard tasks in both the modalities.

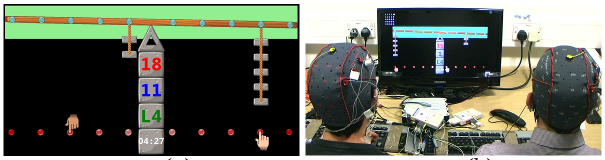
Index Terms— multivariate empirical mode decomposition, multivariate synchrosqueezing transform, intrinsic synchrosqueezing coherence, ear-EEG, hyperscanning

1. INTRODUCTION

One of the most important characteristics of human behaviour is cooperation between individuals. Cooperative human activities require high degrees of mental and physical synchronisation among multiple participants, to the extent that synchrony underpins performance level in activities such as choir singing, playing music in ensemble, rowing, and flying an air plane with a co-pilot. Neuronal synchrony between the participants' brains has been observed through the so-called *hyperscanning* method, whereby cerebral data from two participants is acquired simultaneously, in various cooperative activities, such as imitating hand movements [1], playing the Prisoner's Dilemma game [2], couples of pilots performing flight simulation [3], and musicians playing music in ensemble [4]. An fMRI device was employed for data acquisition in the first hyperscanning study [5], but due to its several limitations, including the size and cost, hyperscanning studies nowadays typically measure neuronal activity by recording electroencephalography (EEG) [1, 3, 4, 6]. The EEG refers to an electrical response which can be non-invasively recorded from the scalp with multiple electrodes. Several EEG hyperscanning studies have shown that the theta (3–7 Hz) and alpha (7–13 Hz) bands are synchronised *between* the brains (inter-brain synchronisation) most during social interaction, and they can be recorded over the right hemispheres of participants, dominating in the right centroparietal regions [1, 2, 6, 7, 8].

A novel EEG recording concept, termed ear-EEG, was proposed in [9, 10, 11]. It allows for the acquisition of EEG signals from inside the ear canal – in-the-ear (ITE) recording – with only a few electrodes and requires relatively short setup time. Several forms of earplugs for the ITE recording system have been introduced in recent years, which include (i) personalised, hard-shell earpieces with silver chloride (AgCl) electrodes [9, 10], (ii) generic earpieces made of silicone and conductive silicone electrodes [12], and (iii) generic earpieces made of a medium-density memory foam and conductive cloth electrodes [13]. These earpieces generally comprise 2 electrodes. The novel ITE earpieces enable the recordings of: (i) alpha activity of EEG (alpha attenuation) [9], (ii) auditory steady-state response (ASSR) [13, 14], and (iii) steady-state visual evoked potential (SSVEP) [13, 15]. However, its capability as an alternative, practical data acquisition approach to the hyperscanning technique has not been explored.

Our recent work [16] proposed a highly localised time-frequency data association measure, referred to as *intrinsic synchrosqueezing coherence* (ISC). This was achieved based on the combination of (i) an adaptive, data-driven algorithm for the analysis of nonlinear and non-stationary multivariate time series, termed noise-assisted multivariate empirical mode decomposition (NA-MEMD) [17], and (ii) algorithms for the generation of highly localised time-frequency (TF) representations of instantaneous amplitudes and frequencies of nonlinear and non-stationary univariate and multivariate signals, termed short-time Fourier transform (STFT)-based synchrosqueezing transform (FSST) and multivariate synchrosqueezing transform (F-MSST) [16]. The NA-MEMD is first employed to obtain physically meaningful intrinsic oscillations, referred to as intrinsic mode functions (IMFs),



(a) *(b)*

Fig. 1. **Screenshot of our cooperative game and experimental setup**. *(a)* Screenshot. *(b)* Setup. The hand on the left was controlled by Subject 1, while the hand on the right was controlled by Subject 2. The red circle dots indicate the positions where the hands can be moved to. The bar was push harder if the hand was further away from the centre. The subjects had to repeatedly push the bar either up or down in order to balance it in the designated green area. The subjects sat in front of a computer screen and were given two separate keyboards for controlling the game.

of a given multivariate signal.[1] The FSST and F-MSST algorithms were next employed to generate highly localised TF representations of synchrony between the intrinsic oscillations produced by the NA-MEMD. The ISC algorithm yields a data association metric which is a function of time, t, and frequency, f, given by

$$SCI_{i,j}(f,t) = \frac{\sqrt{\frac{|T_i(f,t)|\cdot|T_j(f,t)|}{|T_{i,j}(f,t)|}}}{\max_{f,t}\left(\sqrt{\frac{|T_i(f,t)|\cdot|T_j(f,t)|}{|T_{i,j}(f,t)|}}\right)};\forall f,\forall t \qquad (1)$$

where $T_i(f,t)$ and $T_j(f,t)$ are STFT-based *univariate* SST coefficients of IMFs of interest of respectively channels i and j, obtained using FSST, and $T_{i,j}(f,t)$ STFT-based *multivariate* SST coefficients of IMFs of interest of channels i and j, obtained using F-MSST. The synchrosqueezing coherence index (SCI) ranges from 0 to 1, with 0 indicating a non-coherent relationship and 1 the perfect coherence.[2]

The aim of this study is to employ the enhanced discrimination capability of the ISC data association metric, in order to evaluate the performance of ear-EEG against on-scalp EEG as an alternative for practical data acquisition approach for the hyperscanning method in the task of identifying the most robust EEG subbands for inter-individual neuronal synchrony detection for cooperative multi-player gaming. For a full control over the experiment, we have developed our own cooperative multi-player game which was designed to encourage the participants to highly collaborate. While playing the game, the participants' EEG signals were simultaneously recorded

[1]While the simultaneous decomposition of separate artificial WGN channels and the input signal using NA-MEMD, to enforce the dyadic filterbank structure, may hinder the data-driven operation of MEMD, it is however essential in multi-channel operations where the requirement is to compare IMFs with similar centre frequencies and bandwidths in order to preserve the physical meaning of the analysis.

[2]Extensive simulation in [16] on using the ISC algorithm and six other combinations of algorithms to estimate degrees of synchrony in synthetic linear and nonlinear bivariate signals has shown that the ISC algorithm was the most reliable amongst the algorithms considered, since (i) it did not produce spurious synchrony, (ii) its performance increased with SNR, and (iii) it exhibited highly localised synchrony at the frequencies of interest.

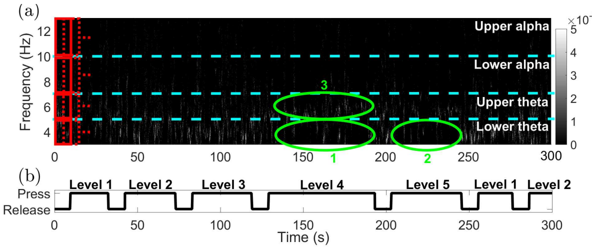


Fig. 2. **Time-frequency inter-brain synchronisation between Couple 1 estimated from ear-EEG recordings**. *(a)* The SCI between Couple 1 for the cooperative trial. *(b)* Time intervals for the 5 levels played in the cooperative trial. The theta and alpha bands, the most relevant bands to inter-brain synchronisation, comprise two subbands: lower (3–5 Hz) and upper (5–7 Hz) theta bands, and lower (7–10 Hz) and upper (10–13 Hz) alpha bands.

with both on-scalp and ITE electrodes. Inter-individual neural synchrony was then estimated using ISC, and a comparison between the two EEG recording modalities was performed, a first step towards fully wearable EEG outside of a lab.

2. METHODS

2.1. Experimental design

We developed a cooperative multi-player game – Bar Balancing – in order for the brains of 6 couples of participants to synchronise as a result of their cooperation while playing the game. The experiment consisted of 3 5-minute trials for the participants to play the game, which comprised 5 levels of difficulty, ranging from 1 (easiest) to 5 (hardest). Before starting each level, the subjects were given 10 seconds to rest. After a level started, the wooden bar was rotating around the pivot point, whereby its rotating speed was determined by the net *virtual* momentum calculated from the number of bricks hanging on both sides of the bar and their positions, that is, the more net virtual momentum, the faster the bar rotated. The amount of net virtual momentum increased from levels 1 to 5 – the wooden bar rotated faster in harder levels. Two separate keyboards were provided to each couple. To complete each level, the subjects were instructed to use pre-defined keys to move the hand further away from or closer to the centre, and to push the bar up or down in order to keep the bar inside the designated area for 20 seconds. For each trial, they were given 5 minutes to complete as many levels as they could. During the first trial, Subject 1 was instructed to play the game alone, while Subject 2 was resting, listening to relaxing music and wearing a blindfold to prevent a phenomenon called 'mirror neurons' [18], which causes undesired neuronal synchrony. The tasks were next swapped in the second trial. The purpose of these two trials was to establish a baseline in neuronal synchrony when no cooperative tasks were performed. During the third trial, a couple were instructed to cooperatively balance the bar and complete as many levels as they could together. Since the levels 4 and 5 were designed to be very difficult to accomplish by a single person, these were the situations in which a couple were expected to highly cooperate,

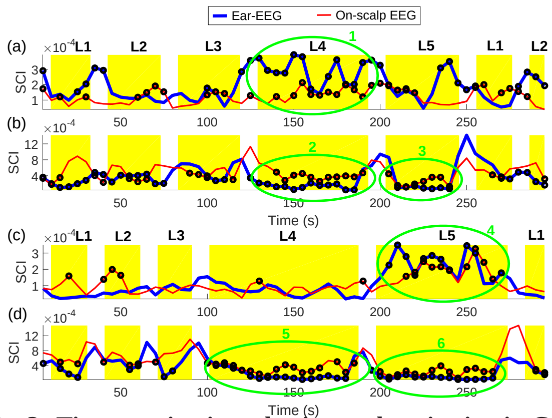


Fig. 3. **Time-varying inter-brain synchronisation in Couples 1 & 2 in the theta band.** *(a)* The SCI of upper theta band of Couple 1. *(b)* The SCI of lower theta band of Couple 1. *(c)* The SCI of upper theta band of Couple 2. *(d)* The SCI of lower theta band of Couple 2. For brevity each level is denoted Lx, with x denoting the level number. Time instants when the couples played each level are depicted by the shaded areas. Significant SCI values are shown in dots.

thus resulting in synchrony in their brain activities. Fig. 1(a) shows a screenshot of the game.

2.2. Data acquisition

The EEG signals were recorded from 6 couples of subjects aged between 24 and 38 years old. The EEG signals of each couple were simultaneously recorded with C4, CP4, P4 on-scalp electrodes, and ITE electrodes inserted into the right ear canals. These on-scalp electrode positions were chosen because they are located over the right centroparietal regions, which were expected to synchronise while the couples were cooperating and are the best possible ground truth for our evaluation. Note that the work in [9] has shown that ITE electrodes exhibit relatively high correlation ($\rho > 0.5$) with the distant on-scalp electrode considered (AFz electrode, located on the forehead) in the increase of alpha activity when the subjects closed their eyes. This strongly suggests relatively high correlation in brain activities between the right ITE electrodes and the electrodes located over the right centroparietal regions, which are closer to the right ears compared to the AFz electrode. All the electrodes were connected to a gtec g.USBamp, 16-channel CE-certified and FDA-listed biosignal amplifier. Generic earpieces used for the ITE recording were made of a medium-density memory foam and conductive cloth electrodes [13]. Fig. 1(b) shows a couple playing the game while their EEG signals were simultaneously recorded.

2.3. Inter-individual neuronal synchrony estimation

The EEG signals of each couple were downsampled from 1200 Hz to 120 Hz, and were combined into 10-channel data which was decomposed using NA-MEMD with 10 adjacent WGN channels. The IMFs produced by the NA-MEMD with indices 2–5 of the 10-channel multivariate EEG signal contained the physically meaningful frequency range 3 to 13 Hz,

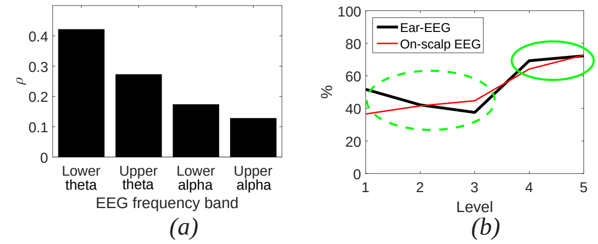


Fig. 4. **Correlation in inter-brain synchronisation between the recording modalities, and average proportion of the number of significant SCI values detected in each level from ear-EEG and on-scalp EEG recordings of the 6 couples in the lower theta band.** *(a)* The ear-EEG and on-scalp EEG recordings were most correlated in the lower theta band. *(b)* For both the recording modalities neuronal synchrony estimated from the lower theta band exhibited distinct discrimination between the easy and hard tasks.

that is, the theta and alpha bands of EEG. The full band of interest in the EEG data was produced by summing up these IMFs, in order to obtain the desired scale in data, and was fed into the STFT-based SST and MSST algorithms for SCI estimation.

3. RESULTS

Fig. 2(a) show SCI values for the cooperative trial between Couple 1 estimated from ear-EEG recordings, and Fig. 2(b) shows the timings of the levels played by Couple 1. Note that Couple 1 finished level 5 within the 5 minutes given, so they played levels 1 and 2 again. Observe two clusters (ellipses 1 & 2) of decreased SCI values in the lower theta band (3–5 Hz) in levels 4 & 5 (the hard tasks requiring cooperation). Since suppression in power (*power desynchronisation*) in the lower theta and alpha bands is believed to be associated with attention [19, 20], the decreased SCI values in the lower theta band suggests synchronised increases in the levels of attention in both of them when simultaneously performing the cooperative tasks. Also, during level 4 a cluster of increased SCI values can be observed in the upper theta band (5–7 Hz, ellipse 3). Since increased coherence in the theta band, particularly the upper portion, between hippocampal and rhinal cortices is correlated with successful encoding of new information into episodic (working) memory [21, 22], we conjecture the increased SCI values in the upper theta band was because working memory also played a role in cooperation, that is, each of the participants subconsciously memorised their actions – the timings of pressing the keys for moving the bar up or down – and adjust them so as to successfully cooperate with the other to keep the fast moving bar inside the designated area.

In order to compare ear-EEG for detecting neuronal synchrony against on-scalp EEG, we calculated average SCI values from 10-second sliding windows with 5-second overlap (5-second increment) in each of the subbands (see the red rectangles in Fig. 2(b)) for both ear-EEG and on-scalp EEG recorded during the same *cooperative* trial. For each sliding window, the Z-test at a significance level of 0.01 was performed, in order to reveal statistical differences in the SCI values between that window and the *whole* corresponding subband in the single-player trial. Since the subjects must be more attentive while cooperating, power desynchronisation in the lower alpha and theta bands, to a different extent, was expected. Therefore, SCI values in these subbands for the cooperative trial were deemed statistically significant if they were statistically *lower* than the SCI values for the corresponding subbands in the single-player trial. Working memory to an extent was also related to the cooperation, increases in power and SCI values in the upper theta bands were therefore deemed significant if they were they statistically *higher* than those for the same subband in the single-player trial. Since power desynchronisation in the upper alpha band reflects semantic memory processes [21, 19], but verbal communication was prohibited during the experiment, semantic memory had no role in the cooperation and the significant SCI values in the upper alpha band – the ones that were statistically lower than those in the single-player trial – do not have any implication on the comparison between ear-EEG and on-scalp EEG.

Fig. 3 shows average SCI values estimated from the lower and upper theta bands of ear-EEG and on-scalp EEG recordings of Couples 1 and 2. Clusters of significant SCI values (black dots) for both the ear-EEG and on-scalp EEG recordings can be observed in levels 4–5 (the hard tasks requiring cooperation) in the lower theta band (ellipses 2 & 3) and in level 4 in the upper theta band (ellipse 1). These conform with the visual observations on the clusters of decreased and increased SCI values for ear-EEG from Fig. 2(b). Clustering in both the recording modalities can also be observed from Couple 2 (ellipses 4–6), and is similar to the clustering of SCI values in the hard tasks for Couple 1. Similar clustering for both recording modalities in the lower theta band can be observed in the other couples (results are not shown), except for Couple 3, where clusters of SCI values were mostly detected through the ear-EEG recording only. Clusters of SCI values in the lower alpha band for all the couples were also mostly detected through only the ear-EEG recording (results are not shown).

Fig. 4(a) shows average correlation (ρ) in time-varying neural synchrony in the 4 subbands between the ear-EEG and on-scalp EEG recordings. The highest correlation in time-varying SCI values between the two recording modalities can be observed in the lower theta band, associated with attention, and the lowest correlation in the upper alpha band, associated with semantic memory. Both the recording modalities were, therefore, most correlated in synchrony detection in the lower theta band. Fig. 4(b) shows average proportion of the number of significant SCI values detected in each level in the lower theta band of all the ear-EEG and on-scalp EEG recordings of the 6 couples. The proportion was calculated by dividing the number of *observed* significant SCI values in that level by the number of *possible* significant SCI values in that level, and the proportion was averaged over the 6 couples. In the lower theta band the proportion of significant SCI values detected was highest in levels 4 & 5 (the hard tasks) for both the ear-EEG and on-scalp recordings (approximately 64% – 72%, see the solid ellipse) compared to only approximately 36% – 51% in levels 1–3 (the easy tasks, see the broken ellipse). This distinct discrimination between the easy and hard tasks was exhibited by both the ear-EEG and on-scalp EEG recordings. For the other subbands, however, similar discrimination by both the recording modalities cannot be observed, and therefore the results are not shown.

4. CONCLUSIONS

This study has employed a novel time-frequency data association measure, termed intrinsic synchrosqueezing coherence, in order to evaluate the performance of ear-EEG against on-scalp EEG as an alternative, practical real-world approach for the hyperscanning technique in the task of identifying the most robust EEG frequency band for inter-individual neuronal synchrony detection for cooperative multi-player gaming. On-scalp EEG recordings were obtained with conventional EEG electrodes placed on the brain regions which were expected to synchronise during the cooperation of 6 couples of subjects. Ear-EEG signals were acquired at the same time, and intrinsic synchrosqueezing coherence (ISC) was then employed to estimate neuronal synchrony between the subjects through both the ear-EEG and on-scalp EEG recordings. Through the estimation of neuronal synchrony produced by the ISC algorithm, both the recording modalities have effectively exhibited power de/-synchronisation in two EEG subbands (lower and upper theta bands) which associate with different cognitive tasks. *It should be noted that an EEG subband which exhibits distinct neural synchrony can vary from task to task, depending upon the cognitive demands.* For the Bar Balancing game, we conjecture that the cooperation was mediated by synchronised attention and, to an extent, adaptive working memory of the participants, reflected respectively by the decreases and increases in significant inter-individual neuronal synchrony in the lower and upper theta bands for both the recording modalities. We also have exhibited that through both the recording modalities the lower theta band was the most robust neuronal marker for brain synchronisation during such a cooperative task, since: (i) it exhibited the highest correlation in neuronal synchrony between the modalities; and (ii) in this subband the proportions of significant neuronal synchrony detected in the easy and hard tasks yield enhanced discrimination ability by both the modalities. It should be noted that this work is a first step towards fully wearable EEG outside of a lab, and therefore did not primarily focus on the understanding of the mechanism of the human brain and its interactions with the others. Future work will focus on: (i) using the Panorama-based ISC algorithm [23] for the enhanced estimation of TF representations of neuronal synchrony from both ear-EEG and on-scalp EEG and (ii) stress analysis to determine the effect of the participants' stress on the cooperative performance.

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