Investigating Brain-Brain Interactions of a Dyad using fNIR Hyperscanning during Joint Sentence Reading Task

Erdinç İşbilir (isbilir@metu.edu.tr)
METU Informatics Institute, Department of Cognitive Science,
Ankara, TURKEY

Murat Perit Çakır (perit@metu.edu.tr)
METU Informatics Institute, Department of Cognitive Science,
Ankara, TURKEY

Fred Cummins (fred.cummins@ucd.ie)
UCD School of Computer Science & Informatics, University College Dublin,
Belfield, Dublin, IRELAND

Hasan Ayaz (hasan.ayaz@drexel.edu)
School of Biomedical Engineering, Science & Health Systems, Drexel University
Philadelphia, PA, USA

Keywords: fNIRS; hyperscanning; neurolinguistics; two-person neuroscience

Introduction

Humans routinely engage in social interaction and joint activities with each other in their daily lives. In such contexts, simultaneous measurement of people's brain activity has recently been suggested as a new methodology suitable for discovering time-locked brain activations of interacting participants in social contexts. In this regard, Schilbach et al. (2013) indicate that even after a decade of successful research in social neuroscience, research on real-time engagement and dynamic interaction between participants remains to be as the so-called "dark matter" of social neuroscience.

Garcia and Ibanez (2014) argue that the new field of two-person neuroscience provides relevant information about brain-to-brain coupling by simultaneously measuring brain activations of multiple participants. The researchers indicate that language-based communication constitutes an important aspect of two-person neuroscience such that language mediates interaction dynamics between the two interlocutors' brains.

An early example of the transformation of research focus from single-subject measurements of brain activations to a multi-brain frame of reference is the study by Montague et al. (2002) where two participants' brain activations were monitored by two fMRI during a social exchange between the participants. In this way, the participants' brain activations during an interaction were simultaneously measured allowing researchers to identify regional patterns of activity correlated between the brains. In this study, the researchers emphasized the importance of hyperscanning in detecting mutual brain activations of the participants in social contexts as compared to single subject studies.

More recently, in the study by Funane et al. (2011), two people's prefrontal cortices were simultaneously monitored by fNIRS during a cooperative task. The participants were told to count 10 seconds in their mind after an auditory cue and to press a button when they finished counting. In addition, the participants were required to adjust their button presses to make them as synchronized as possible. In the experimental condition, the auditory cue was removed thus requiring participants to produce the time interval as synchronized as possible with each other. The results of the study indicated that the spatiotemporal coherence of the brain activations of the participants were observed in medial prefrontal cortex (mPFC) which is a region of the brain activated in tasks that require integration of working memory with attention resource allocation and in processes when people think about other people's intentions.

Similarly, Cui, Bryant, and Reiss (2012) simultaneously measured brain activations of two people using fNIRS while they played a computer-based cooperation game in which pairs of participants completed four separate computer-based tasks. These tasks were cooperation, competition, single 1 and single 2. In the cooperation task, pairs of participants responded to the "go" signal simultaneously. The competition task was similar to the cooperation task except that the pairs of participants were instructed to respond faster than their partner to earn points. In single 1 task, the task was similar to the cooperation task except that the first participant responded while the other passively observed the screen. Single 2 task was similar to Single 1 task except that the second participant responded in this task and the first participant passively observed the screen. The researchers found that the coherence between the participants' signals in their right superior frontal cortices was higher in cooperation than competition condition and increased coherence was associated with better cooperation performance. The increase in coherence compared to competition, single 1 and single 2 tasks was significant in the cooperation task. In addition, the results indicated that learning improved participants' cooperation performance and the level of cross-coherence in their superior frontal cortices.

In terms of a more realistic medium in which there is linguistic exchange between the participants, Silbert, Honey, Simony, Poeppel and Hasson (2014) investigated the coupling of neural systems during production and comprehension of naturalistic speech between speakers and listeners. In this study, the researchers used fMRI to identify the neural responses during production and comprehension of complex real-life speech between speakers and listeners. This study did not use hyperscanning but the speaker's brain activity was recorded first while he was telling a 15-min long real-life story, then 11 listeners' brain responses were scanned while they were listening to the recorded speech. The results of the study indicated that production of speech is not left-lateralized but an extensive bilateral network is activated, and this activation pattern also overlaps with the speech comprehension system. In addition, the researchers analyzed time courses of neural activity during production and comprehension of the same speech and identified neural coupling between the speakers' and the listeners' brain activity in linguistic as well as extra-linguistic areas including medial frontal cortices.

In light of these studies, the present study aims to contribute to this line of research by investigating activation patterns in participants' PFC during a linguistic exchange in which participants simultaneously read Turkish sentences. Specifically, this research aimed to identify behavioral as well as neural correlates of interbrain coherence between participants during a more realistic, linguistic interaction.

The rest of the paper is organized as follows. The experiment design and the fNIRS optical brain imaging technology employed are described in the next section. Then, we present our main findings regarding behavioral synchrony between participants and inter-brain coherence in difference auditory and sentence conditions. The paper concludes with an overall discussion of the results.

Material and Methods

11 male-male pairs in the age range 19-32 participated in this study. The participants were recruited among students of a large public university via ads distributed around the campus. All participants were right-handed as measured by the Edinburgh handedness survey (Oldfield, 1971). None of the participants had a history of psychiatric disorders. Participants were paid 10 TL for their participation. The study was approved by the METU Human Subjects Research Ethics Committee. Written informed consent was obtained from the participants prior to the experiment.

The task comprised of practice and experimental blocks. The participants completed "silent reading practice", "silent reading" and "practice" blocks simultaneously prior to the main experiment blocks. In the main experiment, the participants completed 9 blocks of 7 sentences. In all of the blocks, the sentences appeared on the screen for 15 seconds. Before the sentences appeared on the screen, the participants saw a countdown as 3...2...1 and simultaneously pressed the Space key on their keyboard upon the researcher's verbal guidance, which triggered a 2 second-long fixation screen. In the "silent reading practice" block, participants practiced simultaneously but silently reading three sentences that sequentially appeared on their screens. In the "silent reading" block, participants read 7 sentences simultaneously and silently. In the "practice" block, participants practice simultaneous reading aloud over five sentences. Finally, for each one of the 9 blocks included in the main experiment, participants read a total of 7 sentences. There was one mismatching sentence in blocks 2 – 4 and 6 – 8 for a total of 6 mismatching sentences in the whole experiment. Mismatching sentences differed in only one lexical item, which was located towards the middle of the sentence. There were 20 second-long rest periods between the blocks in the main experiment.

In addition, an audio setup including audio mixers, headphones, and microphones was employed in order to modulate the direction of the auditory feedback available to each co-speaker in a controlled manner. Similar to Cummins et al. (2013) where they implemented three levels of auditory linkage between the participants, the researcher investigated three levels of auditory feedback available to the participants. These levels are SELF, BOTH and OTHER conditions. In the SELF condition, the headphones relay only the speaker's own speech to himself. In the BOTH condition, the headphones relay both speaker's speech at equal volume to each other, whereas in the OTHER condition, the headphones relay only the co-speaker's speech to the other participant.

Moreover, the experimental protocol included matching and mismatching Turkish sentences. The sentences were selected from the METU Turkish Discourse Corpus. All the sentences were in S–O–V sentence frame. The matching sentences were identical to each other while the mismatching sentences differed by one lexical item towards the middle of the sentence. Wuggy (Erten, Bozsahin & Zeyrek. 2014) was used for generating the pseudo-words that replace the lexical item in mismatching sentences.

During the experiment the hemodynamic activity at the prefrontal cortex of each participant was measured with a continuous wave functional near-infrared spectroscopy (fNIRS) system developed at Drexel University (Philadelphia, PA), manufactured and supplied by fNIRS Devices LLC (Potomac, MD; www.fNIRSdevices.com). The system is composed of three modules: a flexible headpiece (sensor pad), which holds 4 light sources and 10 detectors to obtain oxygenation measures at 16 optodes on the prefrontal cortex; a control box for hardware management; and a computer that runs COBI Studio software (Ayaz et al., 2011) for data acquisition (Figure 1).

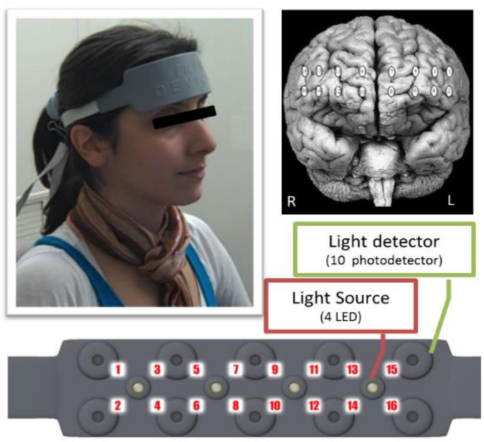

Figure 1: fNIRS sensor (top, left), projection of measurement locations (optodes) on brain surface image (top, right), optodes identified on fNIRS sensor (bottom).

The sensor has a source-detector separation of 2.5 cm, which allows for approximately 1.25 cm penetration depth. This system can monitor changes in relative concentrations of oxy- and deoxy-hemoglobin at a temporal resolution of 2 Hz. The locations of 16 regions on the cortical surface monitored by fNIRS are displayed in Figure 1 above, which correspond to Broadmann areas 9, 10, 44 and 45.

Results

The participant pairs' speech was analyzed for an estimate of asynchrony using a method called dynamic time warping (DTW). This method works by representing each of the speech waveforms that are aligned in real time as a sequence of Mel Frequency Cepstral Coefficients MFCC vectors and then using dynamic time warping to find an optimal deformation that warps one speech waveform onto another. The area under the warping curve that is computed only for the voiced parts of the speech signal provides the quantitative estimate of asynchrony. Dynamic time warping uses one of the speech waveforms as a template onto which to warp the other waveform. In addition, since the analysis is restricted to the voiced parts of the signal, the voiced intervals are determined with respect to the template signal. For this reason, this analysis is conducted twice for each of the signals as being templates for dynamic time warping path and the average value of the areas under the warp curve is calculated and was taken as the asynchrony score. This procedure provides a robust estimate of the asynchrony that is insensitive to microphone characteristics and speaker identity. The participants read two sentences in each block that were used to measure the asynchrony. The MATLAB script developed by Cummins et al. (2013) was used for these computations.

The asynchrony data were log transformed for inferential tests since the data were positively skewed. After log transformation, two-way repeated measures ANOVA where auditory coupling conditions with 3 levels (i.e., self, both, other) and sentence type with two levels (i.e., Sentence 1 and Sentence 2) was conducted.

The results indicated that there was a significant difference among the levels of auditory coupling condition in terms of asynchrony values, $F(2, 82) = 3.380$, $p < .05$, $\eta^2=.076$. There was no significant interaction effect between auditory coupling and sentence type. Pairwise comparisons were computed between levels of auditory coupling condition (i.e., SELF, BOTH and OTHER) with a Bonferroni adjustment of p-values to control for multiple comparisons. The results showed a significant difference between asynchrony in SELF and OTHER conditions.

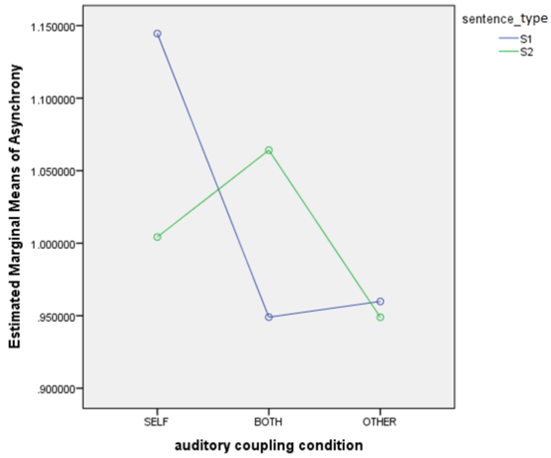

Figure 2: Log-transformed asynchrony across auditory coupling conditions (i.e., self, both, other) and sentence type.

In addition to dynamic time warping analysis, wavelet transform coherence (WTC) was used to evaluate the degree of functional connectivity between the two brains of simultaneously speaking pairs. Wavelet transform coherence is a method to measure the cross-correlation between two time series by decomposing the time series in the frequency-time space (Torrence and Compo, 1998). Wavelet coherence can be interpreted as the local squared correlation coefficient in the time-scale plane. In this regard, wavelet transform coherence is able to identify significant coherence between two brains in a pair of subjects. In the wavelet transform coherence graphs, periods 2-4 (1 Hz – 0.5 Hz) corresponds to heart rate frequency, whereas periods 4-8 (0.5 Hz – 0.25 Hz) were attributable to respiration of the participants. Physiological signals such as heart rate (over 0.5 Hz) and respiration (over 0.2 Hz) are at higher frequency ranges than hemodynamic responses (Ayaz et al. 2011) and therefore were ignored in wavelet coherence analysis. Significant wavelet coherence regions were found in periods 32-64 region (16 s – 32s) which included the period of the blocks (~ 22 s).

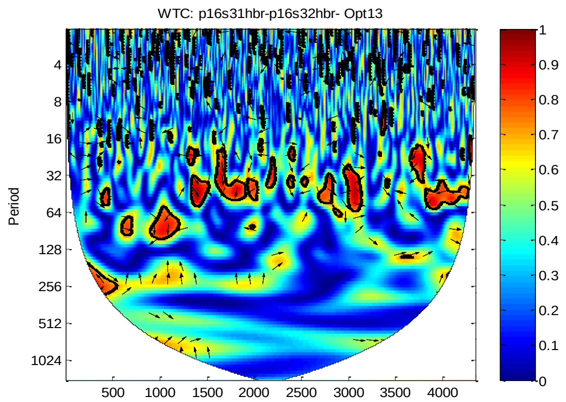

Figure 3: Wavelet transform coherence (WTC) analysis between two raw deoxy-Hb [hBR] signal from optode 13 of the 1st and the 2nd participant in pair 16. The coherence value is between 0 and 1. Significant coherence is indicated by red regions in the graph.

The analyses were based on block design where nine blocks and three auditory conditions were defined for each pair. The coherence values for each block were calculated. The average coherence of all blocks in all participants are as follows:

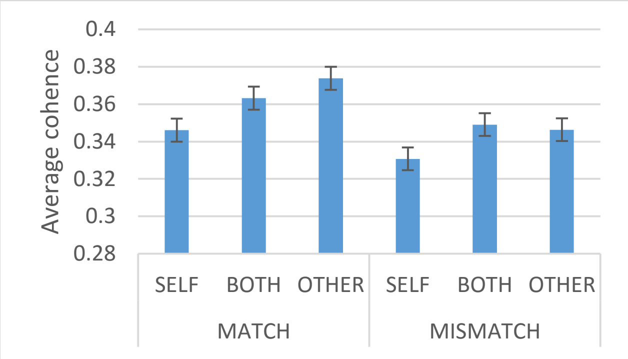

Figure 4: Inter-brain coherence in auditory coupling (i.e., self, both, other) and sentence (i.e., match, mismatch) condition.

In addition to the descriptive results of inter-brain coherence values for auditory coupling and sentence conditions, two-way repeated-measures ANOVA with sentence condition (i.e., match, mismatch) and auditory coupling condition (i.e., self, both and other) was conducted for all pairs. Similar to behavioral results, there was a significant difference among the levels of auditory coupling condition in terms of inter-brain coherence values, $F(2,316) = 7.228$, $p < .01$, $\eta^2=.044$. There was no interaction effect between auditory conditions and sentence conditions. Pairwise comparisons were computed in order to determine the relations between self, both and other levels of auditory coupling in terms of inter-brain coherence.

The pairwise comparisons of auditory coupling conditions in terms of inter-brain coherence showed that SELF condition in which participants' speech was only relayed to themselves generated significantly lower coherence than BOTH and OTHER conditions.

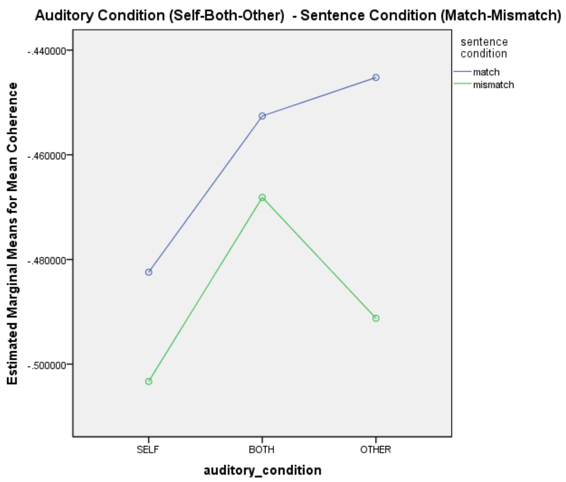

Figure 5: Inter-brain coherence across auditory coupling conditions (i.e., self, both, other) and sentence condition.

Discussion

The results of the dynamic time warping analysis indicated that there was a significant difference in the asynchrony values for auditory coupling conditions with small to medium effect sizes. The obtained results bear similarities to the findings of Cummins et al. (2013) in which they find a difference between SELF and other two conditions (i.e., BOTH, OTHER) for English sentences they used in their study. However, in this study the results only indicated a difference between SELF and OTHER conditions.

In addition to the DTW analyses, the participants' PFC activations were recorded by fNIRS and analyzed by WTC for inter-brain coherence during different conditions of the task. The results showed that for sentence condition (i.e., match, mismatch), the inter-brain coherence was higher in match conditions in which all the sentences were similar for both of the participants than mismatch condition in which one lexical item in the medial position of the sentence was replaced by a pseudoword for one of the participants. Moreover, inter-brain coherence was smallest in SELF condition which is least coupled interaction as compared to BOTH and OTHER conditions. Further, as seen in Figure 5, in match condition, the inter-brain coherence increases as the auditory coupling increases between the participants in the order of SELF, BOTH and OTHER. However, in mismatch condition, inter-brain coherence is lowered in OTHER which is highest auditory coupling between the participants. This particular observation suggests that while participants are simultaneously reading sentences in OTHER condition, a mismatch lexical item affects the coupling of the participants more than it affects in SELF or BOTH conditions.

These findings implicate that behavioral analysis as well as fNIRS hyperscanning is suitable for determining synchrony between participants and monitoring activations in the prefrontal cortex for investigating inter-brain relationships during social interaction. Specifically, fNIRS hyperscanning is effective in determining neural activation patterns for coordination between people during linguistic interactions. In the long term, these findings that are obtained from healthy individuals would inform researchers to further investigate behavioral and neural coupling mechanisms in various other domains where coordination among people is of importance (e.g., learning, education).

References

Ayaz, H., Shewokis, P.A., Curtin, A., Izzetoglu, M., Izzetoglu, K., Onaral, B. (2011). Using MazeSuite and functional near infrared spectroscopy to study learning in spatial navigation. *Journal of Visualized Experiments*, 56, doi: 10.3791/3443.

Cui, X., Bryant, D. M., & Reiss, A. L. (2012). NIRS-based hyperscanning reveals increased interpersonal coherence in superior frontal cortex during cooperation. *NeuroImage*, *59*, 2430-2437.

Cummins, F., Li, C., & Wang, B. (2013). Coupling among speakers during synchronous speaking in English and Mandarin. *Journal of Phonetics*, *41*(6), 432-441.

Erten, B., Bozşahin, C., Zeyrek, D. (2014). Turkish resources for visual word recognition. LREC 2014 (pp. 2106-2110).

Funane, T., Kiguchi, M., Atsumori, H., Sato, H., Kubota, K., & Koizumi, H. (2011). Synchronous activity of two people's prefrontal cortices during a cooperative task measured by simultaneous near-infrared spectroscopy. *Journal of Biomedical Optics*, *16*(7).

García, A. M., & Ibáñez, A. (2014). Two-person neuroscience and naturalistic social communication: The role of language and linguistic variables in brain-coupling research. Frontiers in psychiatry, 5.

Montague, P. R., Berns, G. S., Cohen, J. D., McClure, S. M., Pagnoni, G., Dhamala, M., Wiest, M. C., Karpov, I., King, R. D., Apple, N., & Fisher, R. E. (2002). Hyperscanning: Simultaneous fMRI during linked social interactions. *NeuroImage*, *16*, 1159-1164.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113.

Schilbach, L., Timmermans, B., Reddy, V., Costall, A., Bente, G., Schlicht, T., & Vogeley, K. (2013). Toward a second-person neuroscience. *Behavioral and Brain Sciences*, 36(04), 393-414.

Silbert, L. J., Honey, C. J., Simony, E., Poeppel, D., & Hasson, U. (2014). Coupled neural systems underlie the production and comprehension of naturalistic narrative speech. *Proceedings of the National Academy of Sciences*, *111*(43), E4687-E4696.