Research report

Interindividual synchronization of brain activity during live verbal communication

Kai Spiegelhalder a,∗,1, Sabine Ohlendorf b,1, Wolfram Regen a, Bernd Feige a, Ludger Tebartz van Elst a, Cornelius Weiller c, Jürgen Hennig b, Mathias Berger a, Oliver Tüscher a, c, d

a Department of Psychiatry and Psychotherapy, University of Freiburg Medical Center, Hauptstraße 5, 79104 Freiburg, Germany
b Department of Diagnostic Radiology, University of Freiburg Medical Center, Hugstetterstrasse 55, 79106 Freiburg, Germany
c Department of Neurology, University of Freiburg Medical Center, Breisacherstr. 64, 79106 Freiburg, Germany
d Department of Psychiatry and Psychotherapy, University of Mainz Medical Center, Untere Zahlbacher Str. 8, 55131 Mainz, Germany

HIGHLIGHTS

• Live verbal interaction is accessible to fMRI investigation.
• Activities in speech and listening related areas are coupled between interlocutors.
• The presented methodology may serve to study psychotherapy on a neuronal level.

ARTICLE INFO

Article history:
Received 6 May 2013
Received in revised form 6 October 2013
Accepted 10 October 2013
Available online 18 October 2013

Keywords:
fMRI
Social interaction
Hyperscanning
Dual scanning
Social neuroscience
Psychotherapy

ABSTRACT

Verbal social interaction plays an important role both in the etiology and treatment of psychiatric disorders. However, the neural basis of social interaction has primarily been studied in the individual brain, neglecting the inter-individual perspective. Here, we show inter-individual neuronal coupling of brain activity during live verbal interaction, by investigating 11 pairs of good female friends who were instructed to speak about autobiographical life events during simultaneous fMRI acquisition. The analysis revealed that the time course of neural activity in areas associated with speech production was coupled with the time course of neural activity in the interlocutor’s auditory cortex. This shows the feasibility of the new methodology, which may help elucidate basic reciprocal mechanisms of social interaction and the underpinnings of disordered communication. In particular, it may serve to study the process of psychotherapy on a neuronal level.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Verbal social interaction plays an important role both in the etiology and treatment of psychiatric disorders. A lot of progress has been made with respect to the neurobiological underpinnings of verbal communication [1–4]; however, social neuroscience is still in its infancy. An important limitation of previous studies has been that the neural basis of social interaction has only been studied in the individual brain neglecting the inter-individual perspective. Just recently, functional neuroimaging techniques have been used to investigate neural activities of two interlocutors from an inter-individual perspective [5–12]. However, up to now inter-individual neuronal coupling was not investigated during live verbal interaction although MRI-compatible headphones as well as noise-canceling microphone systems have been developed and used in previous investigations [13–16]. In the current study, we aimed at establishing this hyperscanning method for verbally interacting pairs of participants and investigated, for the first time, live verbal communication using two MRI scanners simultaneously.

2. Methods and materials

2.1. Participants

Twenty-two right-handed women (11 pairs of good female friends; age 27.2 ± 2.9 years) were investigated. All participants were native German speakers, reported no history of psychiatric...
or neurological disorders and were free of any psychotropic medication. All subjects gave their informed written consent prior to inclusion in the study and were compensated for their participation. The study was conducted in accordance with the Declaration of Helsinki and the study protocol was approved by the local ethics committee.

2.2. Procedure

Participants had to speak about or imagine autobiographical events related to descriptions of life episodes. These descriptions were a subsample of those used in a previous study [17] (see Table S1 in supplementary data) and were presented in a pseudorandomized order on a screen behind the participants in the scanner bore using the Presentation® software (Neurobehavioral systems, http://www.neurobs.com/). Three conditions were used in a fixed order: (a) participant 1 had to speak (on-screen instruction for participant 1: “Please speak about: [life episode]”), (b) participant 2 had to speak (on-screen instruction for participant 1: “Please listen”), (c) both participants had to imagine an autobiographical event (on-screen instruction for both participants: “Please imagine: [life episode]”). Each pair of subjects participated in two fMRI sessions, with a 5-min break between sessions. In each fMRI-session, 18 descriptions of life events (six for each condition) were presented for a duration of 44 s. Participants were instructed to finish talking/imaging as soon as the word ‘end’ was presented for 5 s at the end of each episode. Subsequently, two rating scales were presented for 5 s each for ranking arousal (−7 = no arousal to +7 = very high arousal) and emotional valence (−7 = very negative to +7 = very positive) of the previous episode. Participants were instructed to use the left and right buttons of an MRI-compatible computer mouse to move a bar on the horizontally presented rating scales. Finally, a fixation cross was presented for 22 s before the next condition occurred. The timeline of the experiment is presented in Fig. 1.

2.3. Audio transmission

In the MRI scanner, speech was recorded with and transmitted through a dual channel, noise canceling fiber optical microphone system (Optoaoustics Ltd., Or-Yehuda, Israel; www.optoaoustics.com) to suppress gradient noise. This system provides high signal-to-noise ratio (up to 40 dB noise reduction) and high speech quality. Between-scanner transmission of the audio signal was realized by using an internet-based software (http://www.teamspeak.com/) resulting in a short temporal delay with a duration of approximately 500 ms (estimated by using the audio transmission and a telephone connection simultaneously at initial testing). Audio signals were delivered in the scanner by an MRI-compatible set of headphones (MR confon, Magdeburg, Germany, http://www.mr-confon.de/).

2.4. MRI acquisition and statistical analysis

Functional echo-planar images (40 axial slices in interleaved order; slice thickness 3 mm with no gap; voxel size 3 mm × 3 mm × 3 mm; flip angle: 90°; TE: 30 ms; TR: 2.66 s; motion and distortion correction by scanner software [18]) and anatomical images (MPRAGE [19]: TR: 2.2 s; TE: 2.6 ms; voxel size: 1 mm3) were acquired using two 3 Tesla scanners (TIM-Trio, Siemens, Erlangen, Germany) with 8-element head coils in a circularly polarized mode. Functional data were acquired in two consecutive fMRI-sessions of 550 scans each (total scanning time: 48 min 46 s) and analyzed using the AFNI software [20]. Preprocessing included slice timing, coregistration with the anatomical image, normalization into MNI space, smoothing (FWHM, 8 mm), and filtering with a 1/128 Hz high-pass filter. First-level analyses were performed for each subject with the following regressors that were convolved with a standard hemodynamic response function: talking, listening, imagining (each as a block design regressor of 44 s duration), “end” (block of 5 s duration), rating scales (block of 10 s duration), and mouse clicks as occurred (during the presentation of the rating scales). Additionally, the six head movement parameters that were estimated during the online motion correction were used as covariates of no interest. For talking, listening and imagining, 3D images of the individual regression coefficients corresponding to the box-car regressors were entered into second level voxel-wise t-tests (one-tailed). In addition, the average voxel time series of all voxels of the clusters in the left and right primary and premotor cortices that were found to be related to talking (the two clusters with the highest peak activation) were used as regressor in an inter-individual analysis of neuronal coupling. In this analysis, these averaged voxel time series (taken from the ‘predictor participant’) were used as regressors with time shifts −1 TR, 0 TR and +1 TR in the analysis of the interlocutor’s brain (‘predicted participant’) in addition to the above mentioned design-related and movement-related regressors. In order to further control for effects that were induced by the block design protocol, additional inter-individual coupling analyses were carried out in which each individual was paired with a random study participant of the other scanner that was not the actual communication partner. All analyses were carried out for the two fMRI-sessions of 550 scans each. Accordingly, all results including the ones of the inter-individual analyses of neuronal coupling are referring to individuals that were both speaking and listening during the course of the experiment. A Monte-Carlo simulation using the AFNI program “3dClustSim” was performed to estimate the probability of false positive clusters. According to this, overall statistical significance of p < 0.05 was obtained for whole-brain analysis by considering cluster sizes above 567 mm3 (21 voxels) at a voxel threshold of p < 0.001 (T > 3.8). MRcron (http://www.mricro.com/mricroinstall.html) was used for three-dimensional visualization of the results on a ch2better.nii.gz atlas. For subjective measures (valence and arousal), averaged correlation coefficients were calculated both for the actual and random communication partners after the exclusion of the imaging condition. For this purpose, r values of each pair were transformed to Fisher’s z prior to averaging and back transformed averages were reported. The comparison between measures of actual and random communication partners was calculated using t-tests for independent samples on Fisher’s z-values.

3. Results

Average correlation coefficients for valence and arousal scores were higher between communicating participants than between random partners [valence: r = 0.75 vs. r = 0.00; t(31) = 7.51, p < 0.001; arousal: r = 0.45 vs. r = 0.06; t(31) = 4.46; p < 0.001] indicating a successful flow of information during the scanner-to-scanner communication.

3.1. Talking, listening and imagining

As expected, listening was related to bilateral activation of the primary auditory cortex and auditory association areas and talking was significantly associated with bilateral activation of areas related to language generation and speech production (primary motor, premotor, supplementary motor and cerebellar areas). Listening, talking and imagining of autobiographical life events were found to be associated with an activation of the primary visual cortex. Additionally, listening was related to an activation of motor-related areas and a small area in the left inferior frontal gyrus,
talking was related to a bilateral activation of the auditory cortex and the caudate nucleus and imagining was related to an activation of bilateral auditory and motor areas (see Figure S1 and Table S2).

3.2. Coupling analysis of talking-related areas

The average voxel time series of the clusters in the left and right primary and premotor cortices related to talking was used in an analysis of the interlocutor's and a random participant's brain (see Fig. 2). Activity from left and right motor areas were averaged because the time series of these regions were highly correlated within each subject (mean correlation coefficient of 0.89). Of note, the averaged time series were correlated with the box-car regressor for talking (mean r = 0.29). During and after the activation of these talking-related areas in the predictor participant's brain, the primary auditory cortex and auditory association areas were found to be bilaterally activated in the predicted participant. Of note, the time course of activity in a large cluster including the posterior cingulate cortex and the precuneus was also found to be related to the time course of activity in the predictor participant's talking-related areas. In the analysis of random inter-individual coupling, auditory cortex activation was only found in the predicted participant after but not during the activation of talking-related areas in the predictor participant. For simultaneous activation, only small clusters in the parietal cortex and precuneus were found. In addition to these results, a number of small unilateral clusters exceeded the significance threshold in both the analyses of the actual and random communication partners (see Table S2).

4. Discussion

The current study aimed at investigating inter-individual neuronal coupling during live verbal communication. In line with previous studies, the main effects of talking and listening revealed an activation of speech production areas and auditory areas, respectively. Talking-related brain activity was also found in the auditory cortex, possibly reflecting that the speakers heard themselves. Furthermore, listening, talking and imagining of autobiographical life events were found to be associated with an activation of the primary visual cortex, possibly related to the visual presentation of the instruction text or to visual imagery during the experimental conditions.

The inter-individual analysis revealed that the time course of neural activity in talking-related areas was coupled with the time course of neural activity in the interlocutor's auditory cortex. The temporal pattern of this coupling showed that the auditory cortex was activated during and after the activation of the interlocutor's speech production system. This might, in part, reflect the short temporal delay of the audio transmission in the current experiment. However, taking the results of a previous investigation into account [5], it is likely that inter-individual neuronal coupling is characterized by a temporal delay between speakers and listeners. Additionally, activity in talking-related motor areas was associated with a synchronous activation of the PCC and precuneus in the interlocutor's brain, areas that are known to be involved in semantic processing, mentalizing and social cognition [21–23]. When focussing on brain activity in the predicted participant that occurred after the activation of talking-related areas in the interlocutor, the results of the analysis of random inter-individual coupling were similar to but less extended than the ones
of the analysis of inter-individual coupling between actual communication partners. With respect to the two other time shifts, the results of the random inter-individual coupling analysis were not similar to the ones of the main analysis. Accordingly, the analysis of inter-individual coupling between random partners suggests that the results found in the inter-individual analysis with the actual communication partners were not simply induced by the block design protocol but rather by the unique conversation of specific pairs of interlocutors.

In previous fMRI investigations, two communication partners have been scanned one after another during offline interactions, a methodology called pseudo-hyperscanning [5–7]. In the investigation of Stephens et al. [5], inter-individual neuronal coupling between a speaker telling a story and a listener to whom the audiotaped story was presented was only observed when the listener was able to understand the speaker. Moreover, anticipatory speaker-listener coupling was positively correlated with a quantitative measure of story comprehension. Anders et al. [6] investigated inter-individual neuronal coupling between women who were asked to facially express emotional feelings and their romantic partners to whom the videotaped facial expressions were presented. In line with the investigation of Stephens et al. [5], a short temporal delay was observed between neuronal activity of senders and perceivers. Schippers et al. [7] investigated couples who were asked to play the game of charades. The guesser’s brain activity echoed the gesturer’s brain activity in brain areas involved in mentalizing and mirroring. The current study extends this work by providing a novel methodology, fMRI hyperscanning of verbally interacting pairs of individuals.

Some limitations of the current investigation have to be addressed. First, the current study aimed at investigating inter-individual synchronization of brain activity in pairs of individuals who were asked to speak and listen alternately – close to real-life human communication. Therefore, within the context of the current study design, we were not able to dissociate speaker-to-listener coupling from listener-to-speaker coupling. This would
have resulted in analyses based on 44-s-episodes – from our experience with exploratory data analyses, a too short interval to obtain valid results in fMRI coupling analyses. Second, the imagining condition did not provide any information gain with respect to inter-individual neuronal coupling and, thus, should be removed in future studies. Our study was designed with the implicit assumption that inter-individual neuronal coupling could be compared between different conditions (e.g., communication vs. imagining). However, as stated above, the 44-s-episodes turned out to be too short for coupling analyses. Third, neither the signal-to-noise ratio nor the temporal delay of the internet-based audio transmission was investigated systematically. Furthermore, due to the variability of the speed of internet connections we assume that the delay was not perfectly consistent across sessions. Fourth, the current study design did not require ‘true’ hyperscanning and could have been conducted using pseudo-hyperscanning. However, the aim of the study was primarily methodological in nature. Last, the small sample size of the current study may have resulted in a number of false positive findings, especially in those areas that just reached statistical significance.

5. Conclusions

The limitations notwithstanding, the current study extends previous investigations by systematically assessing live dyadic communication in pairs of interlocutors with neuroimaging methods. Additionally, in line with the results of one previous investigation [7], we demonstrated that inter-individual neuronal coupling is not restricted to spatially corresponding areas on which other related studies have focused their analyses [5, 6].

The current investigation represents a first feasibility test which shows that the interaction of neural systems during live verbal communication is in fact assessable via a hyperscanning approach. Pseudo-hyperscanning is limited by the fact that the receiver of information can not influence the sender. Hyperscanning, instead, can be used in future investigations to study the real-time exchange of information between two communication partners allowing to capture the mutual influence of the interaction [12]. This new methodology could open up new avenues of research in social neuroscience possibly elucidating reciprocal mechanisms of disordered communication in psychiatric diseases. It might also become possible to study the process of psychotherapy from a neurobiological point of view, a field that has been dominated by outcome-oriented investigations in the past [24].

Financial disclosures

The authors reported no biomedical financial interests or potential conflicts of interest.

Acknowledgment

The authors gratefully thank Hansjörg Mast, University of Freiburg Medical Center, for his help in conducting the study.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bbr.2013.10.015.

References