The relationship between frontotemporal effective connectivity and performance during auditory working memory task in noise

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**Abstract.** The present study examined the relationship between effective connectivity among frontotemporal brain regions and auditory working memory (AWM) performance. Twenty healthy participants performed a word-based backward recall task in four signal-to-noise ratio (SNR) conditions during functional magnetic resonance imaging scans. Functional data were pre-processed and analyzed using Statistical Parametric Mapping. Optimum connectivity model and strength of effective connectivity were analyzed using Dynamic Causal Modelling. Group results indicated significant brain activation in left superior temporal gyrus (STG) and left inferior frontal gyrus (IFG). Behavioral results showed that performance was enhanced in good SNR but worsened in low SNR. Bayesian model selection showed strong evidence of a bidirectional connection between left STG and left IFG. Correlation analyses showed a moderate positive linear relationship between effective connectivity from left STG to left IFG and behavioral performance. These findings suggest that the strength of effective connectivity from left STG and left IFG may underpin successful AWM performance.

1. Introduction

Arcuate fasciculus (AF) is the white matter tract that connects superior temporal gyrus (STG) and inferior frontal gyrus (IFG) [1]. This connection forms the frontotemporal network that plays an important role in auditory working memory (AWM) processing [2]. The left STG is known for its prominent role in auditory processing [3], whereas the left IFG is crucial for retrieval of semantic and phonological information [4]. Research suggests that noise at a moderate level could enhance AWM performance [5]. However, little is known on how noise affects the effective connectivity (EC) from left STG to left IFG, and whether the EC between these regions underpins successful AWM performance. The present study tested the hypothesis that noise, at a moderate level, enhances performance and that the relationship between EC and behavioral performance is linear. If this notion is true, we expect to see a significant positive correlation between EC and performance.

2. Materials and Methods

2.1. Participants and experimental task
Twenty healthy right-handed male participants (mean age = 21.00 ± 1.52 years) were recruited in this study. They were all native Malay speakers, had normal hearing sensitivity for both ears as assessed using pure tone audiometry (PTA) test, no history of neurological or cognitive disorder, and free from any use of psychoactive medications or stimulants. Written informed consent was obtained from each participant. This study was approved by the Institutional Research and Ethics Committee of Universiti Kebangsaan Malaysia (UKM PPI/111/8/JEP-2017-117). A word-based backward recall task (BRT) was used to assess behavioral performance that required participants to listen carefully to four consecutive words and immediately recalled those words orally in reverse order of presentation. The words were presented for a duration of 4 seconds and participants had to recall within 4 seconds immediately. There was a total of 30 words sequences in each condition. The task was conducted in four different background white noise levels (i.e. 45, 50, 55, and 60 dB SPL) during functional magnetic resonance imaging (fMRI). The target speech signal was presented at 60 dB SPL throughout the presentations. Thus, the signal-to-noise ratio (SNR) of speech information were 15, 10, 5, and 0-dB SNR respectively. The sequence of conditions was pseudo-randomized for every participant. Each condition consisted of 30 stimuli and 30 baseline trials.

2.2. Data acquisition and pre-processing

The functional data were acquired using sparse temporal sampling (STS; [6]). Structural images of the entire brain were acquired using a T1-weighted multiplanar reconstruction gradient-echo pulse sequence. The acquisition parameters were: repetition time (TR) = 1900 ms; echo time (TE) = 2.35 ms; flip angle = 9°; voxel size = 1.0 x 1.0 x 1.0 mm; matrix size = 256 x 256. The functional images were acquired using the following parameters: TR = 10000 ms, TE = 30 ms; acquisition time (TA) = 2000 ms; flip angle = 90°; voxel size = 3.0 mm x 3.0 mm x 5.0 mm; matrix size = 64 x 64. For fMRI, the sparse delay was 8 seconds. Twenty-three transverse slices were acquired parallel to the anterior commissure and posterior commissure plane, in descending order, with no interleave. Functional MRI data were pre-processed using Statistical Parametric Mapping (SPM12; Functional Imaging Laboratory, Wellcome Department of Imaging Neuroscience, Institute of Neurology, University College of London, UK available at https://www.fil.ion.ucl.ac.uk/spm/software/spm12). The first four functional scans were discarded to eliminate magnetic saturation effects. The remaining functional images undergo slice-timing correction, realignment, normalization and smoothing [7].

2.3. Data analysis and dynamic causal modelling

The demographic and behavioral data were analyzed using IBM Statistical Package for Social Science version 21 (SPSS; available at https://www.ibm.com/SPSS/Statistics). A general linear model (GLM) containing the pre-processed images was redefined for each subject and a design matrix was constructed. This design matrix was then estimated and was used in extracting the time series signals from cerebrospinal fluid and white matter centered at (0, -40, -5) and (0, -24, -33) respectively, each with a 6-mm radius volume of interest. The extracted signals from the two regions were then used to construct a new design matrix. The design matrix was then estimated. The design matrix was later used to extract signals from the 6-mm radius sphere of the two regions-of-interest (ROIs); left superior temporal gyrus (L-STG) and left inferior frontal gyrus (L-IFG). The center of each ROI was located at the peak coordinate obtained from the group random-effects analysis (RFX). The time-series signal extracted from the two ROIs were entered into another design matrix, together with the extracted signals from CSF, WM, and six realigned parameters. Three causal models comprising of L-STG and L-IFG were constructed using Dynamic Causal Modelling (DCM12; [8]). Model 1 has a one-directional connection from L-STG to L-IFG. Model 2 has a one-directional connection from L-IFG to L-STG. Model 3 has a bidirectional connection between L-STG and L-IFG. All three models received inputs from the L-STG [9]. The causal models were then estimated to obtain the EC between regions and compared by means of Bayesian Model Selection (BMS) for group studies under the FFX framework. Upon obtaining the most optimum model, the EC values among the two regions were then
averaged over the subjects using Bayesian Parameter Averaging (BPA). A connection is considered significant if its posterior probability value is equal or larger than 0.9.

3. Results and Discussion

3.1. Behavioral data and optimal connectivity model

Group results revealed that participants scored higher during the word-based BRT with 5-dB SNR (mean score = 25.10, SD = 1.41) compared to 10-dB SNR (mean score = 24.20, SD = 1.64, $p = .095$), 15-dB SNR (mean score = 21.90, SD = 1.25, $p < .001$), and 0-dB SNR (mean score = 18.55, SD = 1.19, $p < .001$). These findings indicated that task performance was enhanced in good SNR. The BMS was conducted to test the null hypothesis that no single model is better than any other competing models and to obtain a model that has the best balance between fit/accuracy and complexity. The BMS results for group studies in Figure 1 indicated that model 3 has the highest posterior probability value as compared to the other models across conditions. Therefore, the results indicated that there is a bidirectional connection between the left STG and left IFG.

![Figure 1. Bayesian model selection (BMS) results showing models, relative log-evidence, and posterior probability. Bar graph indicates that model 3 is the optimum model in all conditions.](image)

3.2. Effective connectivity

The BPA results in Figure 2 showed positive EC values from left STG to left IFG. The EC value was highest in 5-dB SNR (.455 Hz), followed by 10-dB SNR (.393 Hz), 5-dB SNR (.111 Hz), and 0-dB SNR (.08 Hz). This finding suggests that activity in the left STG excites activity in the left IFG.

![Figure 2. Bayesian parameter averaging (BPA) results showing effective connectivity between STG and IFG during word-based BRT in (a) 15-dB SNR, (b) 10-dB SNR, (c) 5-dB SNR, and (d) 0-dB SNR. All connections have a posterior probability value larger than 0.9.](image)
3.3. Correlation analysis

Pearson’s correlation coefficient ($r$) was calculated to assess the strength and direction between EC (from STG to IFG) and behavioral performance. The scatterplot in Figure 3 showed that there was a moderate positive linear relationship between the two variables. The results showed a significant ($p < .05$) relationship between EC and performance when the task was performed in 15-dB SNR ($r = .409$, $p = .037$), 10-dB SNR ($r = .432$, $p = .029$), 5-dB SNR ($r = .515$, $p = .010$). These findings indicated that, in good SNR, the strength of EC from left STG to left IFG influences AWM performance. However, in poor 0-dB SNR the correlation was non-significant ($r = .213$, $p = .183$), most plausibly reflects a competition for cognitive resources between noise and useful information [10].

4. Conclusions

In summary, using fMRI, we have examined the relationship between EC from STG to IFG and AWM performance in noise. Behavioral results showed that white noise at good SNR has the capacity to enhance performance. The DCM results indicated that there is a bidirectional connection between the two frontotemporal regions. Also, we have found that enhanced behavioral performance was associated with increased EC from left STG to left IFG. In light of these findings, the present study suggests that good EC from left STG and left IFG is essential for AWM processing.

5. References

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