Psychophysiological interaction between superior temporal gyrus (STG) and cerebellum: An fMRI study

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Abstract. This study aimed to model the psychophysiological interaction (PPI) between the bilateral STG and cerebellum (lobule VI and lobule VII) during an arithmetic addition task. Eighteen young adults participated in this study. They were instructed to solve single-digit addition tasks in quiet and noisy backgrounds during an fMRI scan. Results showed that in both hemispheres, the response in the cerebellum was found to be linearly influenced by the activity in STG (vice-versa) for both in-quiet and in-noise conditions. However, the influence of the cerebellum on STG seemed to be modulated by noise. A two-way PPI model between STG and cerebellum is suggested. The connectivity between the two regions during a simple addition task in a noisy condition is modulated by the participants' higher attention to perceive.

1. Introduction

The psychophysiological interaction (PPI) analysis was aimed to identify regions whose activity depended upon the interaction between physiological factors (the time course of a region of interest) and psychological factors (the tasks) [1]. The principal idea underlying PPI is that if two brain areas are interacting, the level of activity in those areas will correlate over time. In the situation where the correlation coefficient of the two interacting brain areas changes with any experimental factors, PPI can be assumed to exist. We investigated the influence of background (noise) on the connectivity between bilateral STG and cerebellum during the performance of simple addition task in quiet (AIQ) and in noise (AIN) using a functional magnetic resonance imaging (fMRI) technique. The objectives of the study were to determine the psychophysiological interaction (PPI) [1, 2] between the STG and cerebellum in each particular hemisphere and to investigate the influence of background noise in modulating the effective connectivity between STG and cerebellum during a simple addition task in quiet and in noise. If the activity in the STG correlates to that of the cerebellum and vice versa, we should see a linear relationship between the activities of the two regions [3]. If any of the two regions interacts with the experimental factor that exist (such as a noisy condition that distracts attention) in order to exert or to influence the activity in another region, we should see a change in the regression slope on the plot of the response of the second region vs. the activity of the first region [4].

In the present study, we investigated the PPI between STG and cerebellum in both hemispheres during the performance of simple addition task. Subtraction task is not included in this study because the results obtained are assumed to be similar to addition task.

2. Methods

Eighteen native, Malay-speaking, male adults participated in the present study. The average age and standard deviation of the participants were 23.2 ± 2.5 years (ranged between 20 to 28 years). All participants reported no history of the psychiatric or neurological disorder and no current use of any psychoactive medications. All participants were confirmed to be right handed with average laterality index (LI_{ave}) of 87 in the range of sixth to the seventh right. The fMRI data were analysed using statistical parametric mapping (SPM8) [5]. Details about the analysis of the fMRI data are given elsewhere [6]. Bilateral STG and cerebellum were chosen for PPI analysis due to their important roles as processing centre in a task involving auditory and cognitive functions [7]. The PPI analysis was undertaken separately for each hemisphere. The response in one region of interest (ROI), known as the target region, in terms of an interaction between the influence of another ROI, known as the source region and the background condition was investigated. A 4-mm radius sphere (VOI = volume of interest) with the point of maximum intensity as the centre was drawn from each ROI in both quiet and noisy backgrounds. The PPI response in the target region was then plotted as a function of the activity in the source region, assumed to be interacting with the experimental factor (noise) and thereby influencing the response in the target region. PPI is considered to exist if there is a significant change in the slope of the regression line (Friston *et al*. 1997), which is the plot of the response in a target region vs. the activity in the source region, either with or without the interaction with the experimental factor [1]. A simple linear regression analysis was performed using IBM SPSS Version 20 to investigate the interaction between the ROIs in quiet and noisy backgrounds at $p = 0.05$ (95% confidence interval).

3. Results

Figure 1(a) illustrates the response in the right cerebellum plotted against the activity in the right STG, while figure 1(b) shows the response in the right STG plotted against the activity in the right cerebellum, as obtained from the PPI analysis. The best-fit line equation, the R^2 value and the number of participants involved (N) are shown on each of the PPI figures. It can be seen from both plots that the response over the target region (vertical axis) increased linearly and significantly ($p < 0.05$) with the increase in the activity within the source region (horizontal axis) for AIQ and AIN. The activity in the right STG had a similar influence upon the response in the right cerebellum in both conditions as indicated by the same regression coefficient values (figure 1(a)).
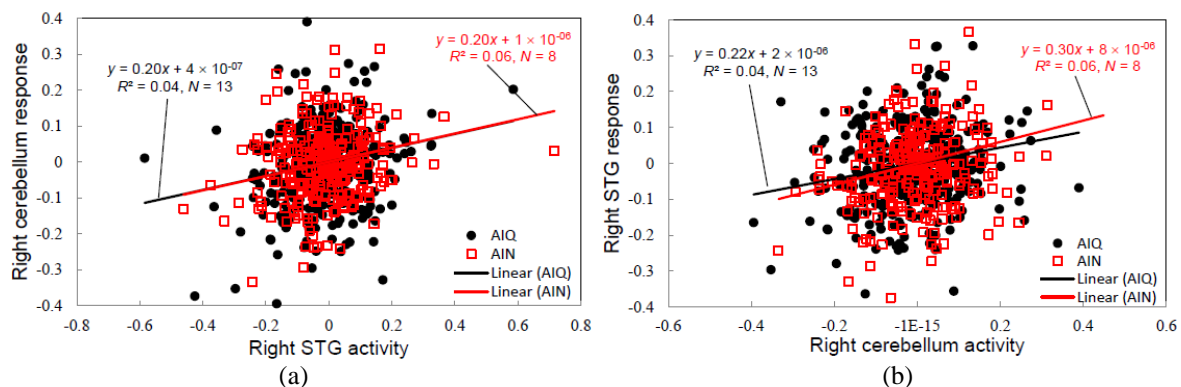

Figure 1. Results of psychophysiological interaction (PPI) analysis between right hemisphere STG and cerebellum for (a) right STG as the source region and (b) right cerebellum as the source region.
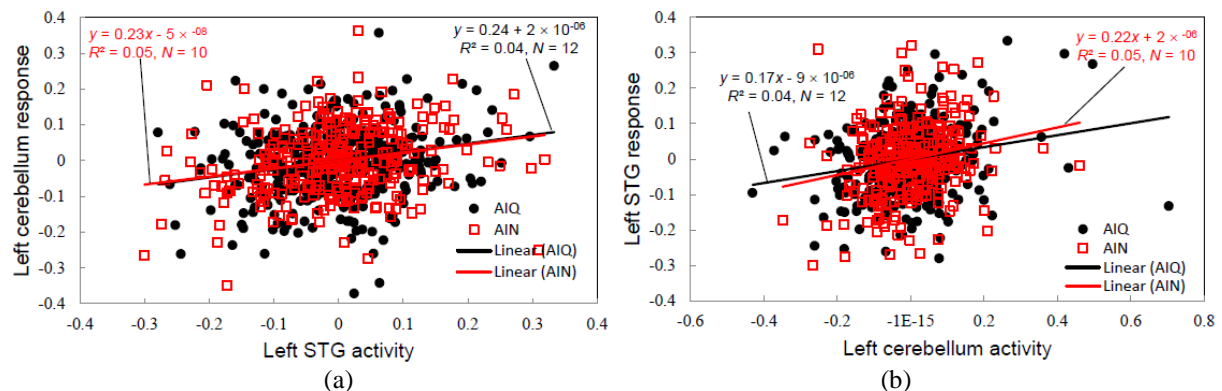
Figure 2. Results of psychophysiological interaction (PPI) analysis during AIQ and AIN between left hemisphere STG and cerebellum for (a) left STG as the source region and (b) left cerebellum as the source region.
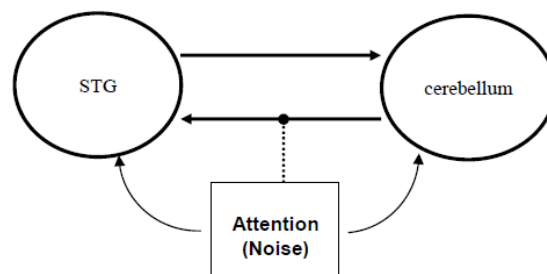

Figure 3. PPI models with attention (noise) to the stimuli as the experimental factor; connectivity from STG to cerebellum is not modulated while connectivity from cerebellum to STG is modulated (dotted line) by the noise.

However, the influence that the right cerebellum has on the right STG during the performance of a simple addition task seemed to increase in noise as compared to in quiet as shown by the steeper slope of the red regression line (figure 1(b)).The steeper slope of the red regression line suggested that noise increased the influence of the cerebellum on the right STG during simple addition task.

Similarly, figure 2(a) illustrates the response in the left cerebellum plotted against the activity in the left STG, while figure 2(b) shows the response in the left STG plotted against the activity in the left cerebellum. The response over the target region (vertical axis) again increased linearly and significantly ($p < 0.05$) with the increase in the activity within the source region (horizontal axis) for both AIQ and AIN conditions. The activity in the left STG also had a similar influence upon the response in the left cerebellum irrespective of whether simple addition was performed in quiet or in noisy condition as indicated by the same regression coefficient values shown in figure 2(a). However, the left cerebellum activity seemed to have some influence on the left STG response that was modulated by the experimental factor (noise) as shown by the steeper slope of the red regression line in figure 2(b).

Figure 3 shows the suggested PPI model that can be used to explain the effective connectivity between the STG and cerebellum during AIQ and AIN with noise as the experimental factor, modulating the influence the cerebellum has on STG but not on the influence the STG has on the cerebellum. Noise, however, had a direct influence on both the STG and cerebellum.

4. Discussion
The PPI between the two areas is presented graphically by plotting the PPI data obtained from the target region against the PPI data obtained from the source region. Figure 1 and 2 illustrate the PPI between

right STG and right cerebellum (lobule VI) and left STG and left cerebellum (lobule VII), respectively. Both figures show that the response over the target region increases linearly with the increase in activity within the source region regardless of the task being performed in quiet (dark line) or in noise (red line). From figure 1 (right hemisphere), it can be seen that there is an increase in the slope (gradient) of the line from 0.22 for AIQ to 0.30 for AIN but only when the right cerebellum (lobule VI) acts as the source region. No change in the slope is observed when STG acts as the source region from which the slope remains at 0.20 for both the AIQ and AIN lines. Similarly, in the left hemisphere, there is an increase in the slope (gradient) of the line from 0.17 for AIQ to 0.22 for AIN, again only when the left cerebellum (lobule VII) acts as the source region. No change in the slope is observed when STG acts as the source region from which the slope remains at 0.24 and 0.23 for both the AIQ and AIN lines respectively. The slope on a line reflects the influence that the source region exerted over the target region. The change in the slope on a plot indicates the presence of PPI [1], with noise (increase in attention) as the experimental factor that modulates the influence that the activity within the source region has on the response over the target region. Thus, a steeper plot slope means that a small change in the activity of the source region results in a relatively larger response over the target region.

Figures 1(a) and 2(a) show that the slope of the AIQ line equals that of the AIN line (STG as the source region and cerebellum as the target region regardless of the hemisphere of the brain). Thus, PPI is not observable in the plots of the response of the right cerebellum (lobule VI) against the activity of the right STG and the response of the left cerebellum (lobule VII) against the activity of the left STG. These results indicate that the connectivity from STG to the cerebellum is not influenced by any experimental factors that exist, which is noise, in this case, see figure 3.

Figures 1(b) and 2(b) show interesting findings (cerebellum as the source region and STG as the target region). The slope of the AIN line is larger than that of the AIQ line for the right hemisphere regions as mentioned above. This is based upon the increase in the slope value when the task is performed in a noisy background (comparing the slope values depicted in figure 1(b)). Thus, PPI is said to be present in the plot of the response of the right STG against the activity of the right cerebellum (lobule VI). These results indicate that the connectivity from the cerebellum to STG in the right hemisphere is influenced or modulated by the experimental factor (noise) that exists, as shown in figure 3. In the presence of distraction such as in a noisy condition, participants' effort in accomplishing the task would increase to overcome the disturbance from the noise which is reflected by an increase in the right cerebellum activity. As a result, the activity within the source region (lobule VI) interacts with the experimental factor (an increase in attention due to noisy condition) and exerts a larger influence on the target region. In the left hemisphere, PPI also appears to exist in the plot of the response of the STG against the activity of the left cerebellum (lobule VII). The influence that the left cerebellum (lobule VII) has on the left STG is also enhanced by the presence of noise. This is based upon the increase in the slope value when the task is performed in noise (comparing the slope values depicted in figure 2(b)). It can be said that the activity within the source region (lobule VII) interacts with the experimental factor (noise) and exerts a larger influence on the target region. The suggested PPI model is shown in figure 3. The experimental factor also has a direct influence on the respective regions. In the absence of noise, participants would be able to listen to the given stimuli better without any needs to increase their attention to overcoming distraction, which is shown by the smaller slope value.

In the present study, bilateral STG and cerebellum were chosen to be the source and target regions (interchangeably) due to their important roles in arithmetic working memory [8]. On the one hand, STG is assumed to act as the input centre for auditory processing whereby auditory signals from sub cortical areas were received before being transmitted to other cortical areas for further processing [9]. In addition to that, STG has been well-known about its role in processing verbal (e.g. speech or word numbers) and non-verbal (e.g. pure tones and noise) stimuli [6]. On the other hand, earlier imaging studies have highlighted the role of the cerebellum in working memory processes and various other processes related to attention [10], in addition to its well-known role in coordinating motor movement [11].

In this study, one of the experimental factors to be considered is the 80-dB white noise in which the 83-dB stimuli are embedded. The presence of the noise during the task performance increases the difficulty for the participants to listen to the delivered stimuli thus forcing the participants to increase their efforts to overcome distraction in order to accomplish the task, e.g. paying more attention to the given stimuli [12]. Interestingly, the presence of noise only affects the connectivity from cerebellum to STG either in the right or left hemisphere (figure 3) but not the other way around. As mentioned above, the main role of STG is to process sound stimuli that are delivered through the two ears [9]. The information gathered in the STG is then transmitted to other brain areas depending upon the type of task being executed, regardless of whether the task is performed in a quiet or in a noisy background. In other words, the information that was sent to the cerebellum is not affected by the noise. These explain why the connectivity from STG to the cerebellum is free from being influenced or modulated by the interaction between the noise and the activity in the STG. In contrast, in solving the arithmetic addition problems in a noisy background, cerebellum comes into play due to its cognitive functions such as for attention and language [13]. Furthermore, the cerebellum is involved in attenuating noise and/or increasing attention to task performance and is connected to STG in the process [14]. Thus, it is quite reasonable to suggest that the information that was sent back to STG from cerebellum was modulated by the interaction between the experimental factor (noise) and the activity in the cerebellum itself.

5. Conclusion

PPI results indicated that the connectivity from STG to the cerebellum in both hemispheres is not influenced by the experimental factor. In contrast, the connectivity from the cerebellum to STG is modulated by the interaction between the activity of STG and the experimental condition, e.g. noise. This suggests that the persisting interaction when the cerebellum acts as the source region is modulated by the noise which could be due to the increase in attention in order for the participants to get a better perception of the stimuli in a noisy surrounding. These results strengthen previous findings on the involvement of the bilateral cerebellum in arithmetic working memory processing and might be useful in explaining brain performance in suppressing irrelevant information for patients with disordered brain function.

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