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The Effects of Background Noise on Brain Activation During a Verbal Working Memory Task

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ABSTRACT

This study was carried out to investigate the effects of noisy background on brain activation during a working memory task. Fourteen healthy male subjects underwent silent functional Magnetic Resonance Imaging (fMRI) scans while listening to words presented verbally against quiet (WIS) and noisy (WIN) backgrounds. The stimuli were binaurally presented to the subjects at 70 dB sound pressure level (SPL) in both conditions. Group results indicated significant ($p < 0.001$) bilateral widespread of brain activations in the primary auditory cortex, superior temporal gyrus, inferior frontal gyrus, supramarginal gyrus and inferior parietal lobes during WIS. Additional significant activation was observed in the middle cingulate cortex and anterior cingulate cortex during WIN, suggesting the involvement of cingulate cortex in working memory processing against a noisy background. The mean percentage of signal change in all regions was higher during WIN as compared to WIS. Right hemispheric predominance was observed for both conditions in primary auditory cortex and middle frontal gyrus and this could be attributed to the increased difficulty of the tasks. The results obtained from this study demonstrated that background noise increased task demand and difficulty. Task demand was found to play an important role in determining the activation magnitude in the brain areas during working memory task.

Keywords: Functional magnetic resonance imaging; auditory; working memory; noise

INTRODUCTION

Working memory refers to a temporary storage that involves maintenance and manipulation of information during higher cognitive processes such as language comprehension, spatial processing, mental arithmetic, planning and reasoning [1,2]. Based on Baddeley's and Hitch's model, working memory consists of a central executive with two support systems which are phonological loop and visuo-spatial sketch pad [2]. The phonological loop plays an important role in the linguistic processes involving articulatory rehearsal and phonological storage. On the other hand, the visuo-spatial sketch pad includes tasks with visual and spatial information. To date, a vast number of studies investigating brain activation during working memory task [3,4] have been conducted.

It is known that background noise will cause difficulty in understanding speech. The ability to understand speech in noisy conditions is one of the important skills for effective communication. The presence of noise would modulate what is perceived[5] and only if the listener knows the topic of conversation can a successful verbal communication be achieved [6]. The reduction in the ability to understand speech in noise is one of the characteristics of individuals with learning disabilities, and this is related to the higher cognitive process such as working memory [7]. Previous studies on working memory used reading span, n-back, pitch memory and item recognition tasks [8,9]. However, these studies did not focus on how working memory is accomplished in noise despite the fact that background noise degrades communication. There have been several studies conducted to examine the effects of noise on cortical activation. However, most of these studies focused on speech perception [10-12]. Previous studies suggested that listening to speech in noise increases brain activation in the auditory regions, especially the superior temporal gyrus (STG). STG has been found to play an important role in processing speech and spectrally complex non-speech signals [13, 14]. However, the role of STG in separating the signal from noise is still unclear. F:for example, how the underlying neural network processes and interprets verbal information [10].

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In the present study, we explore brain responses to verbal working memory task using auditory stimulus presented in noise and in silence. A sparse functional magnetic resonance imaging technique was used to capture the brain responses. We hypothesised that performing working memory task in noise requires more effort, which would result in an increase in activation characteristics in all regions of interest, especially in the temporal and frontal cortices.

MATERIALS AND METHODS

Subjects

Fourteen young, healthy Malay males with normal hearing and within the age range of 20 to 40 years (mean 20.05±4.04 years) participated in this study. The subjects were right-handed as assessed by Edinburgh Handedness Inventory [15]. The subjects were given informed consent and screening forms as required by the Institutional Ethics Committee (IEC). The subjects' middle ear condition was examined using a tympanometer (Model Grason Stadler Inc. GSI33). A pure tone audiometer (Model Grason Stadler Inc. GSI61) was then used to assess current hearing threshold in a range of 250 – 8000 Hz. Both the audiometry assessments were carried out by a qualified audiologist. All the subjects had bilateral hearing threshold not greater than 30 dB across the test frequencies.

Data Acquisition

Functional magnetic resonance imaging (fMRI) examinations were performed using a 1.5 tesla magnetic resonance imaging (MRI) system (Siemens Magnetom Avanto) equipped with functional imaging option, echo planar imaging capabilities and radiofrequency (RF) head coil used for signal transmission and reception. Gradient Echo – Echo Planar Imaging (GRE-EOI) pulse sequence with the following parameters were applied: repetition time (TR) = 16000 ms, acquisition time (TA) = 5000ms, echo time (TE) = 50 ms, field of view (FOV) = 192 × 192 mm, flip angle (α) = 90°, voxel size = 3 × 3 × 3 mm^3, slice thickness = 3 mm. In addition, anatomical images of the entire brain were obtained using a T1-weighted spin echo pulse sequence with the following parameters: TR = 1620 ms, FOV = 250 × 250 mm, α = 90°, voxel size = 3 × 3 × 3 and slice thickness = 1 mm.

Stimulus

A sparse or silent imaging paradigm (Figure 1) was used in this study in order to eliminate the effects of the scanner sound on the functional MRI images [16]. The auditory stimuli were presented for six seconds during the 11-s gap

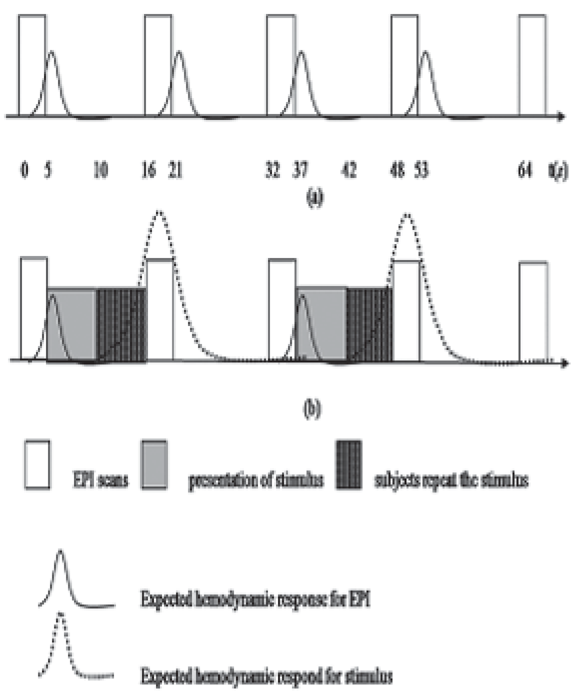


Figure 1. Schematic representation of the experimental paradigm (a) functional echo planar imaging (EPI) at 16-s using silent fMRI acquisition paradigm and (b) with working memory task.

of scanner silence between successive acquisitions. There were two types of auditory stimuli, verbal words in quiet (WIS) and verbal words embedded in noise (WIN). The verbal words consisted of Malay language noun words with two syllables (for example, 'buku', 'kayu', 'kain', 'bola', 'meja') which were randomly presented. For WIN, words were embedded in speech noise at -3dB SNR. The noise was taken from the Hearing in Noise Test (HINT)[17]. The stimuli were given via a headphone which was connected to a digital playback system and presented binaurally at intensities of 70 dB sound pressure level (SPL).

Behavioural Tasks

During the fMRI experiment, the subjects performed the two working memory tasks WIN and WIS. The subjects were instructed to listen, memorise and repeat the words in correct order. The subjects were given 5s to respond to the given stimulus and asked to press the rubber bulb after repeating the words. This was done in order to ensure that the subject remained focused throughout the entire scanning session. Subjects' performance in both conditions was scored as the percentage of the words that had been correctly repeated. Paired t-test at significant level of (α) 0.05 (two-tailed) was used to determine the difference between the two conditions.

Image Analysis

The fMRI images were analysed using a matlab (MATLAB 7.4 – R2007a (Mathworks Inc, MA, USA)) based Statistical Parametric Mapping programming software (SPM8) (Functional Imaging Laboratory, Wellcome Department of Imaging Neuroscience, Institute of Neurology, University College of London). The image volumes from each subject were re-aligned to the first image in the time series to correct for movement related artefacts. The images were then normalized to a stereotactic MNI reference space and smoothed with an 8-mm full-width-at-half-maximum (FWHM) Gaussian kernel. A conventional analysis based on the general linear model (GLM) was used on each voxel to generate brain activation in the regions of interest. For group analysis, the random effect analysis (RFX) was used and the statistical inference was made at significant cluster level (a) of 0.05.

Region of Interest Analyses

To further investigate the differences between the two conditions, a region of interest (ROI) analysis was performed. Five functional ROIs were chosen, and these were the primary auditory cortex (PAC), superior temporal gyrus (STG), inferior frontal gyrus (IFG) identified as Brodmann area (BA) 44 and 45 and inferior parietal lobe (IPL). These ROIs were anatomically defined based on the probabilistic cytoarchitectonic maps as implemented in the SPM anatomy toolbox (http://www.fz-juelich.de/ime/spm_anatomy_toolbox). Regions not defined by the probabilistic maps based on cytoarchitecture, were defined by Automated Anatomical Labelling (AAL) [18]. For each individual, the percentage of signal change (PSC) was calculated from each ROI in both hemispheres for both conditions. A correlation analysis between subjects' accuracy scores and PSC in all five regions was conducted to further investigate the relationship between brain activation and behavioural performance.

RESULTS

Behavioural Data

Figure 2 shows the group mean accuracy in repeating the given words during the working memory tasks in the two conditions: listening to words in silence and in noise. Subjects were able to carry out the task with high performance accuracy (88%) in a silent condition. However, the performance accuracy is reduced (72%) in a noisy condition. A significant different was found between both conditions (paired t-test $|t| = 7.644$, $n = 14$, $p < 0.001$). Post hoc pair wise comparison showed that subjects' responses were less accurate in noise than in quiet.

SPM Results

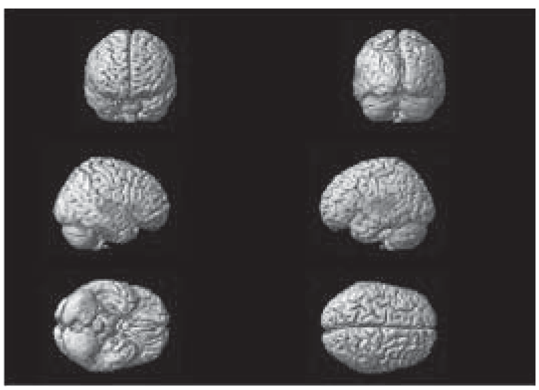
During WIS, the activated voxels were found in PAC, STG and middle temporal gyrus (MTG) in the temporal lobes in both hemispheres. Activated voxels were also found in the frontal and parietal regions. Bilateral frontal regions exhibited the most dominant activity mainly in the inferior frontal gyrus which consists of BA44 and BA45. Significant activations were also found in the cerebellum, precentral gyrus and postcentral gyrus as shown in Figure 3(a).

Figures 3(b) shows brain activation in working memory task during WIN. Similar activation was also found in the temporal, frontal and parietal lobes as well as in the cerebellum. In addition, WIN indicates activation in

Figure 2. Bar chart showing a significant different (p<0.001) in the participants' behavioural performance between two conditions. Error bars indicate standard errors of the mean.

the anterior cingulate cortex (ACC), middle cingulate cortex (MCC), supplementary motor area (SMA) and the right middle frontal gyrus (MFG). WIN activated a relatively larger area in both hemispheres. These activations were extended into the frontal and parietal regions. When compared to the right hemisphere, the left hemisphere elicited much larger activation in both conditions.

A paired t-test was applied to identify the differences in brain activation between WIN and WIS, that is, voxels that are activated during WIN but not during WIS during the working memory task. The results indicated



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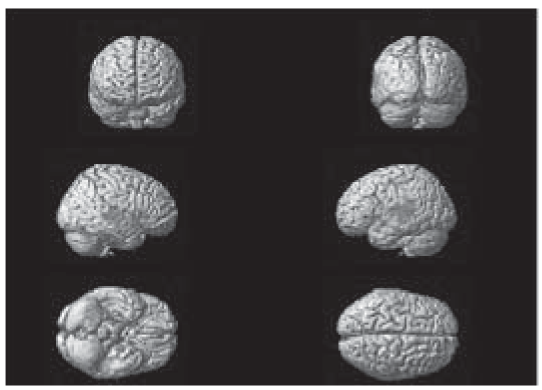

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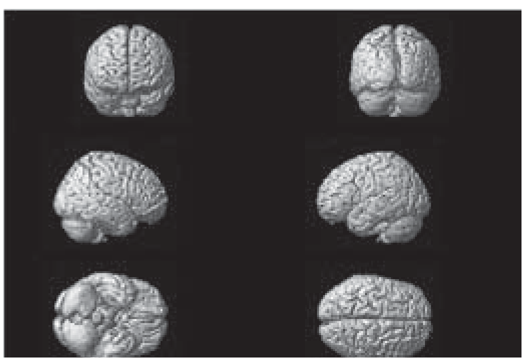

(a)

Figure 3. Brain activation from group random effect analyses (p<0.001) during working memory task in (a) WIS versus baseline, (b) WIN versus baseline and (c) WIN versus WIS.

significant ($p < 0.05$) clusters in the anterior cingulate cortex (ACC), and middle cingulate cortex (MCC). Table 1 summarises the significant activation areas relative to baseline obtained from RFX ($p < 0.05$) for words presented in quiet (WIS) and in noise (WIN) in the working memory task.

Table 1. The location of major activation areas in the MNI coordinates (x, y, z)

Area	x	y	z	t-value
WIS vs. baseline				
Left STG	-48	-34	16	11.61
Left IFG	-34	24	-6	5.71
Left Rolandic Operculum	-40	-34	18	9.18
Left Cerebelum	-12	-62	-20	8.65
Left Postcentral Gyrus	-54	-12	24	7.78
Left SMA	-4	10	46	4.79
Left Precentral Gyrus	-28	-10	66	4.96
Right IFG	54	24	-6	8.72
Right STG	46	-26	10	10.04
Right insula	40	22	0	7.63
Right IPL	46	-42	46	6.41
Middle Cingulate Cortex	6	18	40	4.31
Right Cerebelum	32	-56	-30	11.08
Right SMA	8	14	46	5.04
Right Postcentral Gyrus	52	-6	30	4.60
WIN vs. baseline				
Left Superior Temporal Gyrus	-62	-26	4	16.18
Left Middle Temporal Gyrus	-68	-40	6	8.08
Left Insula Lobe	-34	24	-4	8.33
Left Inferior Frontal Gyrus	-36	24	-2	4.97
Middle Cingulate Cortex	0	24	34	6.18
Left SMA	0	10	46	5.52
Left Rolandic Operculum	-40	-32	16	9.09
Left Cerebelum	-12	-64	-22	9.44
Left Superior Parietal Lobule	-28	-60	46	6.74
Left Inferior Parietal Lobule	-28	-56	38	5.33
Right Superior Temporal Gyrus	62	-22	2	10.67
Right Inferior Frontal Gyrus	48	18	-14	9.46
Right Middle Temporal Gyrus	52	-32	-6	8.74
Right Insula Lobe	36	20	4	9.78
Right Inferior Parietal Lobule	50	-42	48	7.42
Right SupraMarginal Gyrus	46	-40	42	6.05
Right Precental gyrus	50	10	40	6.70
Right Postcentral gyrus	58	0	22	4.48
Right SMA	8	6	66	5.09
Right Middle Frontal Gyrus	36	8	54	4.95
Middle Cingulate Cortex	2	26	32	6.31
Right Cerebelum	26	-58	-32	10.29
WIN vs WIS				
Anterior Cingulate Cortex	4	28	28	5.47
Middle Cingulate Cortex	-28	26	34	4.79

ROI Analysis

Figure 4 shows the mean PSC for all ROI based on the cluster with highest activity in all 5 regions. For each subject, PSC for each experimental condition was entered into 2 × 2 (Hemisphere × Condition) repeated measures ANOVA. The results showed the main effect of hemisphere in PAC $F(1,13) = 13.491$, $p < 0.01$ STG $F(1,13) = 5.554$, $p < 0.05$, IPL $F(1,13) = 4.762$, $p < 0.05$ and a significant condition × hemisphere interaction in IFG, $F(1,13) = 5.269$, $p < 0.05$. Brain activation was larger for WIN than for WIS in PAC, STG, IPL and left IFG. However, paired sample t-test showed no significant effect of condition in all regions. Due to ACG being significant during

WIN>WISand to further investigate the role, paired sample t-test was done and the results showed there was a significant difference between WIN and WIS ($p < 0.001$).

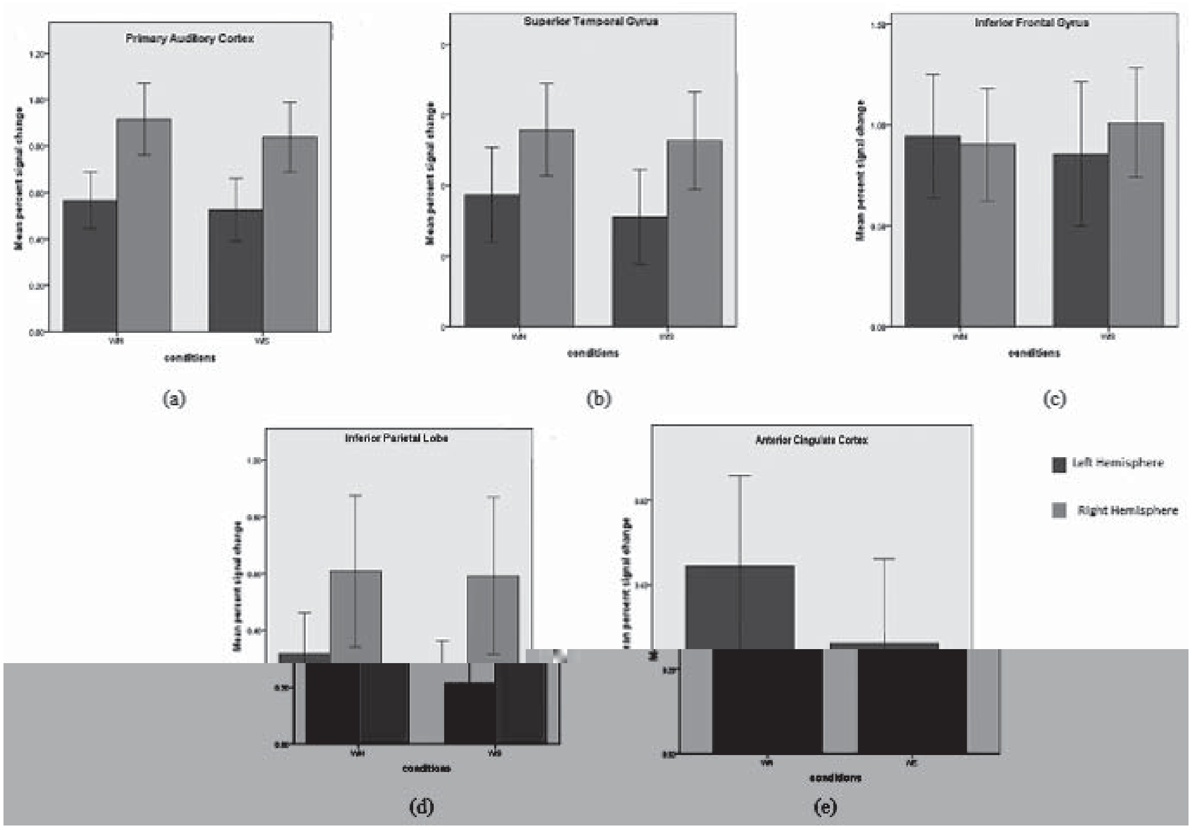

Figure 4. Percentage of signal in five regions (a) primary auditory cortex (PAC) (b) superior temporal gyrus (STG) (c) inferior frontal gyrus (IFG) (d) inferior parietal lobule (IPL) and anterior cingulated cortex (ACG).

Correlation Analysis

It was found that only the left STG showed a significant correlation (Pearson's -0.422, $p < 0.05$; see Figure 5).

DISCUSSION

Many previous neuroimaging studies highlighted the role of temporal, frontal and parietal regions during verbal working memory tasks[8,19]. However, little is known about the effects of noise on the brain responses in these regions. This study attempted to explore brain activation in these regions in response to verbal working memory tasks presented in noise and in silence.

In the present study, both conditions revealed a robust bilateral activity in the temporal lobes, especially in the STG (Wernicke's area), PAC and MTG. It has been hypothesised that the PAC detects the basic acoustic signals whereas the secondary auditory cortex plays an important role in processing speech and complex non-speech stimuli[20]. Based on previous neurological studies, speech perception was thought to reside in the temporal regions whereas speech production function was ascribed to the inferior frontal regions via Broca's region[21,22]. The findings also revealed the existence of connection between the left posterior temporal and left frontal articulatory systems which support speech production, including the ability to repeat heard speech[23]. Additionally, based on Baddley's model, rehearsal process which serves to support maintenance in the phonological store was ascribed to Broca's area which consists of BA44 and BA45. These regions, which have been consistently activated in this study, were similar to what had been found in other studies which involved performing phonological decision tasks such as phoneme monitoring and discrimination or sequencing[24]. Bilateral activation was also observed in the parietal lobes. These regions have been demonstrated to be engaged when verbal information needed to be recalled from working memory regardless of the types of verbal item (e.g., letters, words or digits) to be remembered[25]. Brain

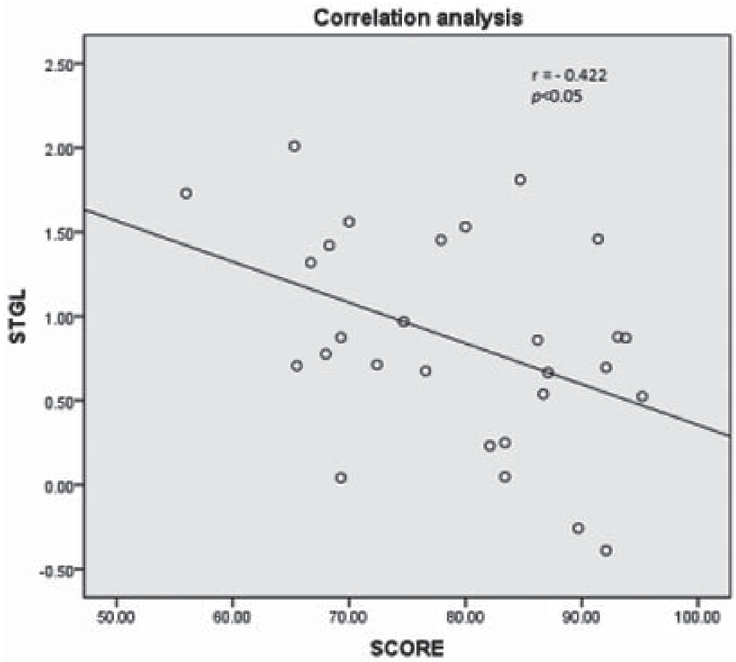

Figure 5. Correlation between score and left STG.

activations were also found in the postcentral gyrus, precentral gyrus and SMA. These areas are believed to be involved in verbal planning and also in the initiation of speech[26].

SMG and MCC have also been reported to be activated in several neuroimaging studies concerning working memory processing and have been suggested to play significant roles in phonological storage[27]. Activations were also observed in left frontal and parietal regions. This suggests that these areas are associated with the controlled cognitive processing in storing and manipulating information with the involvement of attentional mechanisms. As the subjects listened to the stimulus, they also needed to maintain information before executing the task. Therefore, significantly larger activation was observed in the frontal and parietal regions.

Even though ANOVA results show no significant effect between conditions, the PSC in all the ROIs shows slightly higher activations in noisy condition as compared to in silence. This shows that the presence of noise has affected the speech, especially in the way the brain receives and processes the information. A study[12] that examined brain activation corresponding to speech in three listening conditions, which were in quiet, in moderately loud noise and in loud noise, found that in both left and right auditory cortex, an increase in activation was observed in noisy condition, implicating the engagement of auditory-attentional network. Words embedded in noise would also increase the task difficulty. Therefore, higher cognitive effort and attention was needed to complete the task and this was consistent with the behaviour results that showed a lower accuracy when the subjects performed working memory tasks in noise.

The differences in brain activation between working memory in noise and silence reveals an increased activity in ACC. The role of ACC in working memory has been documented in many previous studies. One study reported that, during hard condition the activation was shifted to the cingulate gyrus[28]. It suggests that this area is recruited to overcome the effects of noise embedded in the speech. ACC is also believed to mediate response selection, conflict processing or allocate attentional resources when faced with competing sources of information[10]. However, such patterns of activations were not seen when speech in noise was contrasted with speech in silence in other studies, which revealed activation only in the right parietal cortex and left prefrontal cortex[14] and STG, MTG, insula and precentral gyrus[12]. However, it is noteworthy that these studies only explored the neural basis of speech perception.

For between hemisphere comparisons, results showed higher brain activations in the right hemisphere in both conditions except for IFG. This is not in accordance with other studies that involved speech stimulation especially in temporal lobe. The absence of left hemispheric activation could be due to the type of stimuli used in the present study. In addition, it has been reported that the right hemisphere is always engaged when performing difficult behavioural tasks[29]. In this study, the subjects needed to memorise the words within a few seconds, hence increasing the difficulty of the tasks. A previous study which also observed the same trend of activation suggested that speech sound processing in noisy condition will decrease the involvement of the left hemisphere and increase the involvement of the right hemisphere[28].

Parietal lobes, which often activated during working memory tasks, have been assigned to storage processing especially in the left hemisphere. However, in this study, brain activation was also observed in the right hemisphere. This may indicate an involvement of parietal mechanism in shifting attention, where subjects needed to change their focus from words in silent to words in noisy condition.

The result shows left STG had a negative correlation between PSC and score, which means the less accurate the subjects in perceiving the words, the higher the STG activation. These showed that more effort was needed in more difficult tasks. However, other studies[29] in speech perception concluded that the more accurate the participants were in receiving the word in noise, the higher the STG activation which reflected the quality of sensory information and the effort in overcoming noisy condition.

CONCLUSION

In summary, the results obtained from this study show that multiple cortical regions were involved during the verbal working memory task in quiet as well as in noisy condition. The results support the fact that brain activity in most of the regions exhibited greater activity when performing working memory tasks in noisy conditions. We also found that cingulate cortex plays an important part in processing speech in noisy condition. However, it is still unknown whether this region is involved in attention system or in differentiating noise and speech. Therefore, more studies need to be conducted in order to further understand how this region contributes in the working memory task.

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