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Low intensity white noise improves performance in auditory working memory task: An fMRI study

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ABSTRACT

Research suggests that white noise may facilitate auditory working memory performance via stochastic resonance. Stochastic resonance is quantified by plotting cognitive performance as a function of noise intensity. The plot would appear as an inverted U-curve, that is, a moderate noise is beneficial for performance whereas too low and too much noise attenuates performance. However, knowledge about the optimal signal-to-noise ratio (SNR) needed for stochastic resonance to occur in the brain, particularly in the neural network of auditory working memory, is limited and demand further investigation. In the present study, we extended previous works on the impact of white noise on auditory working memory performance by including multiple background noise levels to map out the inverted U-curve for the stochastic resonance. Using functional magnetic resonance imaging (fMRI), twenty healthy young adults performed a word-based backward recall span task under four signal-to-noise ratio conditions: 15, 10, 5, and 0-dB SNR. Group results show significant behavioral improvement and increased activation in frontal cortices, primary auditory cortices, and anterior cingulate cortex in all noise conditions, except at 0-dB SNR, which decreases activation and performance. When plotted as a function of signal-to-noise ratio, behavioral and fMRI data exhibited a noise-benefit inverted U-shaped curve. Additionally, a significant positive correlation was found between the activity of the right superior frontal gyrus (SFG) and performance in 5-dB SNR. The predicted phenomenon of SR on auditory working memory performance is confirmed. Findings from this study suggest that the optimal signal-to-noise ratio to enhance auditory working memory performance is within 10 to 5-dB SNR and that the right SFG may be a strategic structure involved in enhancement of auditory working memory performance.

1. Introduction

Working memory is part of the central executive process that allows information to be temporarily stored and manipulated in mind [1]. A well-functioning working memory is crucial for learning and academic performance [2]. Auditory information, such as sound and speech, is processed by a sub-system called auditory working memory (AWM [3]). Noise has traditionally been considered as interference which detriments AWM performance [4]. It has been assumed that noise distracts one's attention from a target task [5], due to competition for attentional resources between noise and useful information [6]. However, research also suggests that noise at a moderate level has the capacity to facilitate cognitive processing [7, 8, 9, 10]. The phenomenon in which adding external noise improves cognitive performance is known as stochastic resonance (SR [11]). SR is quantified by plotting detection of cognitive performance as a function of external noise level [5]. The plot appears as

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an inverted U-curve function, where performance peaks at a moderate noise level [12].

It is worthy to note that the optimal white noise level to enhance cognitive processing may differ across individuals. For instance, children with attention-deficit hyperactivity disorder (ADHD) and children rated as sub-attentive by their classroom teachers showed significant improvements in cognitive performance during exposure to white noise but had but no significant effect on normal healthy children [7, 8]. The differential effects of white noise observed between individuals may be explained with the moderate brain arousal model (MBA [13]). The MBA model postulates that individual differences in cognitive performance are associated with the level of background neural noise [14]. The MBA model also proposed that sub-attentive children and those with ADHD have lower neural noise levels as compared to their typically developed peers. In such cases, it has been predicted that adding external noise via perceptual system could increase the neural noise level, and possibly, result in enhanced cognitive performance [15]. This prediction was investigated and confirmed in various subject groups and tasks. For instance, children with ADHD showed significant improvements in span board and word recall tasks (stimuli were presented visually) during exposure to white noise at 80 dB as compared to in quiet [7]. In another study, sub-attentive children performances in word recall and word recognition tasks (stimuli were presented auditorily at 75 dB) were highest during exposure to white noise at 70 dB (5-dB SNR), as compared to in white noise at 65 (10-dB SNR) and 75 dB (0-dB SNR) [8].

As most studies examined the effect of white noise in individuals with attentional problems [7, 8], studies on the effects of white noise on cognitive performance in healthy individuals are scarce and demand further investigation. Despite the previous claim that the presence of white noise may not be beneficial for healthy individuals as they have optimal neural noise level [16], recent findings suggest otherwise. For instance, white noise at 70 dB was found to enhance new world learning (stimuli were presented visually) in healthy young adults [9]. In an auditory study using 55 dB multi-talker babble noise, healthy young adults showed a significant improvement during word-based backward recall task (BRT) in 5-dB SNR as compared to in quiet [10]. However, the optimal noise level to improve cognitive performance, particularly in the auditory domain of healthy individuals remain unclear. The main aim of the current study was to extend this line of research by examining the within-subject effects of white noise on AWM performance in healthy young adults. The objectives of this study were two-fold. First, to test the hypothesis that moderate white noise can improve AWM performance through the phenomenon of SR. If this is correct, we expect to see a significant increment in performance in the presence of a moderate noise level. Second, we used functional magnetic resonance imaging (fMRI) to understand how the AWM neural networks respond when performing tasks in the presence of different SNR. We would also expect to see an increase in the spatial and height extent of brain activation in the frontal cortex, primary auditory cortex, and other AWM-related brain areas. Brain activation was also correlated with the BRT scores to assess a possible relationship between behavior and brain activity.

2. Materials and methods

2.1. Participants

Twenty healthy young male volunteers aged between 18 and 24 years (mean age = 21.00 years, SD = ±1.52 years) were recruited from local higher learning institutions via community advertisement. We recruited only male participants due to the existence of gender differences in working memory networks [17]. The participants were native Malay speakers and had normal hearing sensitivity for both ears, as assessed by pure tone audiometry (PTA). Their absolute hearing threshold was equal or less than 20 dB HL in the frequency range of 250 Hz to 8 kHz. The participants were right-handed, as assessed by the Edinburgh Handedness Inventory [18]. From self-report assessment, all participants were free from the history of recurring otitis media and of neurological or cognitive disorders. The participants also claimed to be non-musician and not to have previous experience of playing any musical instrument professionally. Participants were also selected from a non-musician background as it has been suggested that musicians have greater speech perception and outperform non-musicians in perceiving speech at varying noise levels [19]. The participants were screened for psychoactive medications or stimulants use. Each participant was briefed on the details and risks of the study. Written informed consent was obtained from each participant prior to the study. This study was approved by the Institutional Ethics Committee of the Universiti Kebangsaan Malaysia (Reference number: UKM PPI/111/8/JEP-2017-117) and National Medical Research and Ethics Committee (Reference number: NMRR-17-56-33800). Each volunteer was given an honorarium of 50 Malaysian Ringgit (MYR 50) for their participation.

2.2. Auditory stimuli

The targeted-speech signal and background white noise were generated and edited using version 2.1.3 of Audacity® software (available at https://www.audacityteam.org). The targeted-speech signal consisted of 40 meaningful, but unrelated, typically-known Malay words. The words were matched for word length and phonological similarity to ensure consistency throughout the experiment. The word length effect refers to the finding that monosyllabic words are recalled better than multisyllabic words [20]. In order to avoid word length effect, all words used in this study were bi-syllabic (i.e., matching for word length). Since this study involves the AWM, it was important to consider the phonological similarity effect as words that sound almost similar were found to be harder to be recalled than those which sound distinctly different [21]. In order to avoid the phonological similarity effect, each word sequence consisted of dissimilar items (i.e. matching for phonological similarity). The words were spoken by a native Malay female speaker and were digitally recorded inside a sound-proof room. The recorded audio files were later edited to remove unwanted background and static noises. The variation in sound level of each word was normalized. The intensity level (measured in dB SPL) of the targeted-speech signal was adjusted to 60 dB SPL. The bandwidth of the generated white noise was from 43 Hz to 21491 Hz. The intensity level of the background white noise was set at 45, 50, 55, and 60 dB SPL. The targeted-speech signal was then embedded within these different intensity levels of white noise resulting in signal-to-noise (SNR) of 15-dB SNR, 10-dB SNR, 5-dB SNR, and 0-dB SNR respectively. The sampling rate of the auditory stimulus was 44.1 kHz with 32-bit float. To ensure that audio output produces the same sound level for every participant, the sound level was measured every time the audio file is played. This was done using a digital sound level meter (model MS6708; complies with IEC651 Type 2 and ANSI S1.4 Type 2) adjusted to record on a slow setting. No discrepancies were detected in the sound levels.

2.3. Experimental task

This study used an auditory word-based backward recall task (BRT [10]) to assess participants' AWM performance. This task was specifically chosen as it requires maintenance and manipulation of verbal auditory information [20]. Participants were required to listen carefully to four consecutive words and immediately recalled those words orally in reverse order of presentation. For example, the correct answer for the word sequence "apple – hammer – towel – market" would be "market – towel – hammer – apple." Similar to that in the previous studies [22, 23, 24], the number of words per sequence was limited to four as participants tend to make errors when the number of words exceeds six [25]. It was important in this study to ensure that errors made by participants were due to the increase in noise level, and not to the difficulty of the task itself. It has been proposed that three to five meaningful items are optimal to tax the working memory in young adults [26]. In every word sequence, the words stimuli were presented for a duration of 4 s and participants were given 4 s afterward to respond. We chose to limit response time to 4 s because unlimited processing times do not measure higher-order cognition such as the working memory [27, 28]. Each word sequence was only used once in each condition. Participants were given a correct score if they correctly recalled all the four words in reverse order within the 4 s duration. Scores were manually recorded on score sheets by the same researcher inside the magnet room. Fig. 1 illustrates the experimental task paradigm.

2.4. Procedure

After completing and passing the hearing test, the participant performed an offline word-based BRT in a sound-proof room in the absence of noise. This session, also known as the "quiet" condition, was conducted before the actual fMRI scanning session to obtain the baseline BRT score for all participants. Prior to performing the task, a list containing all the chosen words was shown to the participants for familiarization in order to avoid systematic behavioral confounds [10]. The baseline score was compared with the score obtained in the noise conditions to determine whether behavioral performance decreased or increased in the presence of noise. The task was then conducted on a separate day inside a 3 T S Magnetom Verio MRI system equipped with functional imaging capabilities at the Department of Radiology, Universiti Kebangsaan Malaysia Medical Centre. Participants were thoroughly screened for any MRI contraindications. We used NordicNeuroLab MRI-safe headphones (available at https://www.nordicneurolab.com) for transmission of binaural auditory stimuli and noise attenuation. They were also instructed to minimize the movement of their head during image acquisition to avoid motion artifact and to close their eyes during the task to avoid additional demands related to visual processing. The task was conducted in the morning to control for circadian rhythm and time-of-day effects [29, 30].

2.5. fMRI imaging paradigm

Sparse temporal sampling (STS [31]) was used during image acquisition to allow for auditory stimuli to be presented during the silent interval between acquisitions, and to eliminate the effects of scanner noise [32]. STS is an ideal fMRI data acquisition technique for auditory studies as it allows auditory stimuli to be effectively delivered even at low intensities [33]. The BRT was conducted in four experimental runs: (i) 15-dB SNR, (ii) 10-dB SNR, (iii) 5-dB SNR, and (iv) 0-dB SNR. Each run, or condition, consisted of 30 trials and 30 baselines. For STS, 30 trials per condition were thought to be adequate for sufficient signal detection, as the optimum number of trials should fall between 12 and 36 [34]. The duration of each trial was 10 s. The scan time for each condition was 10 min. In between runs, participants were given 2 min for relaxation. The total scan time was approximately 50 min. The sequence of conditions was pseudo-randomized for every participant. The echo-planar imaging (EPI) acquisition time (TA) was 2 s and the repetition time (TR) was 10 s. Baseline duration was 8 s, during which participants were instructed to rest and relax their minds. During the baseline, neither word stimuli nor white noise was presented. Fig. 2 illustrates the STS imaging paradigm.

2.6. Data acquisition

Structural images of the entire brain were acquired in high resolution using a T1-weighted multiplanar reconstruction spin-echo pulse sequence. A 128-channel phased-array radiofrequency head coil was used for signal transmission and reception. The acquisition parameters were: TR = 1900 ms; echo time (TE) = 2.35 ms; flip angle = 9°; voxel size = 1.0 × 1.0 × 1.0 mm; matrix size = 256 × 256. The functional images were acquired using an EPI pulse sequence to produce T2*-weighted images. The acquisition parameters were: TR = 10000 ms, TE = 30 ms; TA = 2000 ms; flip angle = 90°; voxel size = 3.0 mm × 3.0 mm x 5.0 mm; matrix size = 64 × 64. For fMRI, the sparse delay was 8 s. Twenty-three transverse slices were acquired parallel to the anterior commissure and posterior commissure plane, in descending order, and with no interleave. The total number of active and baseline volumes acquired for all conditions was 240.

2.7. Data pre-processing

Functional MRI data were pre-processed in MATLAB 9.3 - R2017b (MathWorks Inc., MA, USA; https://www.mathworks.com/products/matlab) and Statistical Parametric Mapping (SPM12) (Functional Imaging Laboratory, Wellcome Department of Imaging Neuroscience, Institute of Neurology, University College of London, UK; https://www.fil.ion.ucl.ac.uk/spm/software/spm12). The first four EPI scans were discarded to avoid magnetic saturation effect [35]. The remaining functional images were corrected for slice acquisition delay [36]. The time-corrected images were then realigned to the first image of each session to account for head motion artifact and to remove image drift using a six-parameter affine transformation in both translational (*x*, *y*, and *z*) and rotational (pitch, roll, and yaw) directions. The head movements threshold (for exclusion) were set at maxima of 2 mm in translational and 2° in rotational [37]. All participants' head movements did not exceed the threshold. The data were then normalized to the Montreal Neurological Institute (MNI) template brain using a 12-parameter affine transformation as implemented in SPM12. The normalized images were spatially smoothed using a 3D Gaussian kernel with full-width at half-maximum of 8-mm. A high pass filter was applied at the cut off frequency of 1/128 Hz to eliminate low-frequency fluctuations caused by aliased biorhythms, cardiac effects, and other oscillatory signal variations.

2.8. Data analysis

2.8.1. Demographic and behavioral data

Demographic and behavioral data were analyzed using IBM Statistical Package for Social Science (SPSS; available at https://www.ibm.com/SPSS/Statistics) version 21. The demographic data included age and years of education. The behavioral data included the BRT score obtained by participants across all conditions. Shapiro-Wilk test was used to test

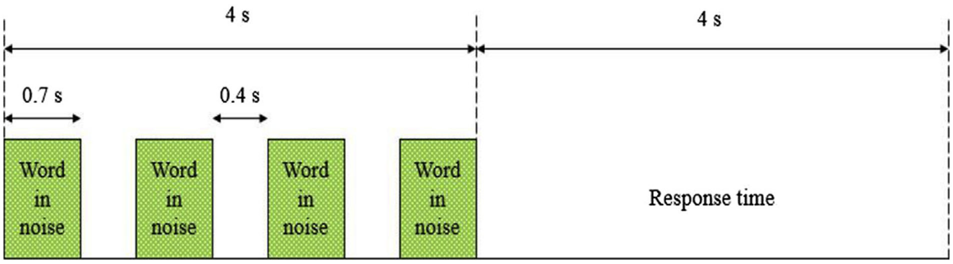

Fig. 1. Stimulus sequence for word-based backward recall task (BRT). Four consecutive words each with a 0.7-second duration separated by a 0.4-second silent gap made up a 4-second stimulus train.

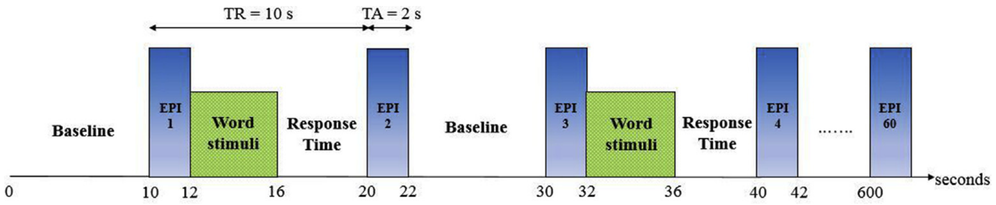

Fig. 2. Schematic representation of the timing diagram for STS. Volume acquisition began by acquiring baseline measurement (EPI 1), followed by active measurement (EPI 2). The volumes were acquired every 10 s and each volume was acquired for a duration of 2 s.

for data normality. A one-way independent analysis of variance (ANOVA) was conducted to test for a quadratic contrast across noise levels. Post-hoc Tukey's HSD test was later conducted to determine if there was any significant difference in mean scores between conditions.

2.8.2. *fMRI data*

A whole-brain analysis was conducted using SPM12 to determine significantly activated brain areas evoked during BRT in noise and to explore patterns of activity across conditions. Individual functional data were analyzed using a conventional first level fixed-effect analysis (FFX). Five regressors were included in the design: (i) 15-dB SNR, (ii) 10-dB SNR, (iii) 5-dB SNR, (iv) 0-dB SNR, and (v) motion parameters. The estimated motion parameters for each participant were included as covariates of no interest to minimize spurious activations due to head motion and to increase statistical sensitivity. These regressors were convolved using the hemodynamic response function. The four noise levels were contrasted (separately) against the silent baseline during interstimulus interval, generating a statistical parametric map with the following contrasts: (i) 15-dB SNR > baseline, (ii) 10-dB SNR > baseline, (iii) 5-dB SNR > baseline, (iv) 0-dB SNR > baseline. These contrasts yielded overall brain activity patterns evoked during BRT in noise minus baseline. To further investigate for differences between SNR conditions, additional analyses were performed to compare the activation of brain regions in one condition relative to another. The single-subject contrast images were then used in the second-level random effects analysis (RFX), generating a group statistical parametric map ($P_{\mathrm{FWE}} < 0.05$; with family-wise error correction for multiple comparisons). Voxel-level thresholding was not applied to ensure all active voxels which survived the statistical threshold were included in the analyses. All clusters which survived this threshold were regarded as significantly activated cortical brain region.

A region of interest (ROI) analysis was conducted using WFU PickAtlas [38] to assess the spatial extent of brain activation (in terms of the number of activated voxels) in specific brain areas [39]. The ROIs included in the analysis were selected based on their prominent roles in AWM processing. These were superior temporal gyrus (STG), Heschl' s gyrus (HG), superior frontal gyrus (SFG), middle frontal gyrus (MFG), inferior frontal gyrus (IFG), and anterior cingulate cortex (ACC). STG and HG are part of the primary auditory cortices (PAC) and were selected due to their dominant role in auditory processing [39, 40]. In addition, SFG, MFG, and IFG were chosen as they are part of the prefrontal cortex (PFC) and are involved in working memory processing [41]. We have also included ACC, as this area has been suggested to be involved in sustained attention [42]. The ROI analysis was conducted on individual functional data. Single-subject anatomical atlas was used to define image volume masks for each ROI (bilaterally) [43]. The mask was then applied onto the individual statistical parametric map set at the statistical threshold of $P_{\mathrm{FWE}} < 0.05$ to obtain activation statistics of that particular region. The number of activated voxels (NOV) was extracted from the area with the highest *T*-value (peak MNI coordinate) within the ROI. For each participant, the NOV obtained for every contrast and in each ROI was recorded and analyzed in IBM SPSS. A one-way independent ANOVA was used to ascertain the effects of noise on the NOV and to determine if the effects were statistically significant for all conditions. Then, Pearson's correlation coefficient (r) was calculated to see if there is a linear brain-behavior relationship.

3. Results

3.1. *Demographic and behavioral data*

Shapiro-Wilk test was non-significant ($p > .05$), indicating that age (mean age = 21.00 years, SD = ± 1.52 years) and years of education (mean years of education = 14.00 years, SD = ± 1.52 years) were normally distributed, and demonstrating homogeneity of variances. The mean number of correct recalled word sequence obtained in each condition (maximum score of 30 per condition) are tabulated in Table 1. Shapiro-Wilk tests were non-significant ($p > .05$) in all conditions, indicating that the behavioral scores were normally distributed. Furthermore, Mauchly's test indicated that the assumption of sphericity was not violated ($p = .238$). The one-way independent ANOVA revealed a significant effect of noise level on behavioral scores $F\,(4{,}95) = 63.40$, $p < .001$. Levene's test was non-significant, indicating that the variances for the BRT scores in all conditions were approximately equal and that the assumption of homogeneity of variance has not been violated $F\,(4{,}95) = .218$, $p = .928$. There was a significant quadratic trend, $F\,(4{,}95) = 65.32$, $p < .001$, indicating that the pattern of means was curvilinear. As shown in Fig. 3(a), the interpolation line exhibited an inverted U-shaped function. Post-hoc Tukey's HSD test in Table 2 further revealed that the participants scored significantly better during the word-based BRT in 10-dB SNR and 5-dB SNR as compared to the same task in quiet ($p < .005$, Bonferroni corrected for multiple comparisons).

3.2. *fMRI data*

The whole-brain analysis showed that performing word-based BRT in four different SNRs activated bilateral STG, HG, SFG, MFG, IFG, and ACC. Additionally, activations of the precentral gyrus, superior parietal lobule, inferior parietal lobule, middle temporal gyrus, insular cortex, claustrum, thalamus, putamen, and cerebellum were also identified. Fig. 4 illustrates the brain activation pattern, height extent of activation (t statistics), coordinates of maximum intensity, and the number of activated voxels (NOV) obtained for each ROI. The mean NOV obtained over all participants for each ROIs are plotted as in Fig. 5. The results from one-way independent ANOVA in Fig. 5 showed a significant quadratic trend ($p < .05$) for the NOV in the left HG, bilateral SFG, MFG, IFG, and right ACC across SNR. Additionally, results revealed a significant main effect of noise on the

Table 1
Backward recall task (BRT) scores obtained from 20 participants.

Condition	SNR	Background noise level	Target-speech level	Mean ± SD
Baseline	60-dB SNR	0 dB SPL	60 dB SPL	21.20 ± 1.54
1	15-dB SNR	45 dB SPL	60 dB SPL	21.90 ± 1.25
2	10-dB SNR	50 dB SPL	60 dB SPL	24.20 ± 1.64
3	5-dB SNR	55 dB SPL	60 dB SPL	25.10 ± 1.41
4	0-dB SNR	60 dB SPL	60 dB SPL	18.55 ± 1.19

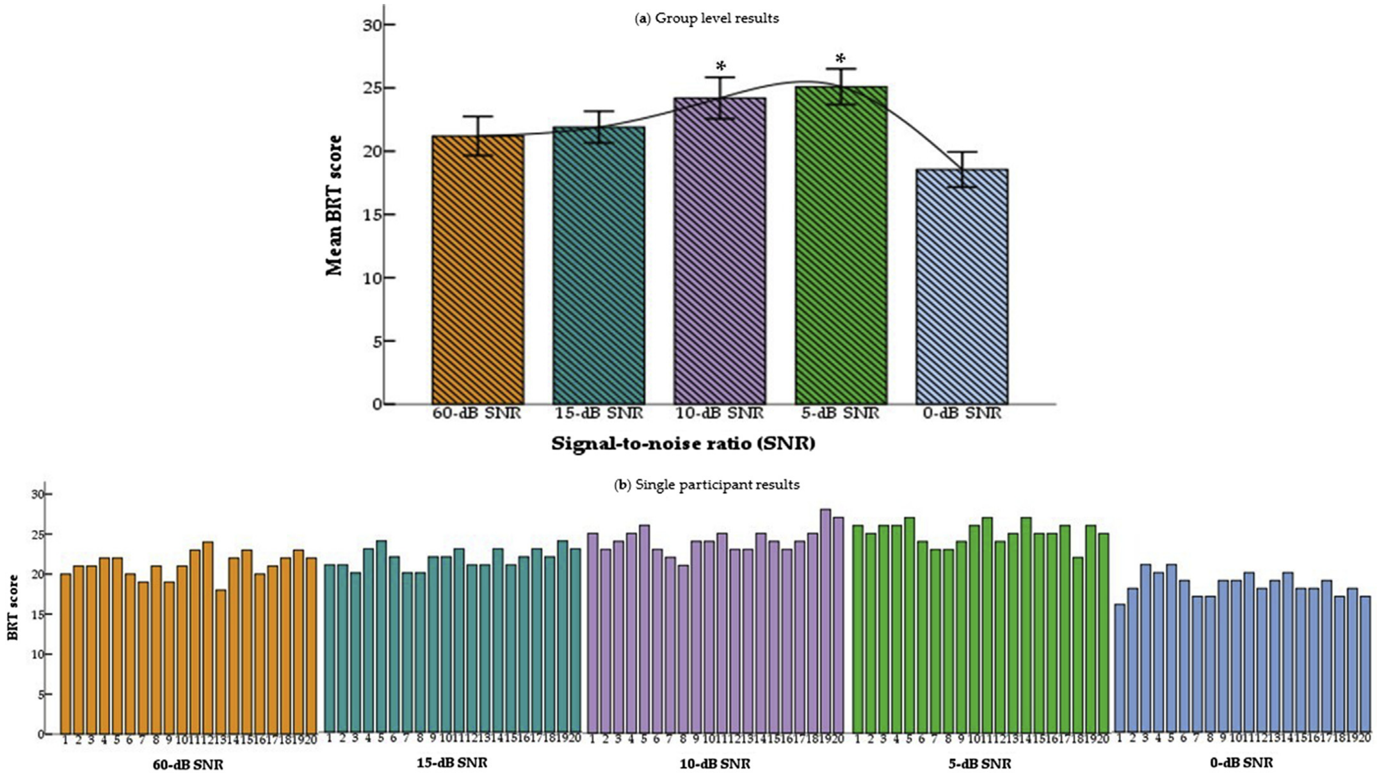

Fig. 3. The number of corrected recalled word sequences as a function of signal-to-noise ratio (SNR). The bar graphs show (a) group-level results obtained from 20 participants during BRT in four different SNRs. The interpolation line depicted the noise-benefit inverted U-curve shape. Asterisk mark indicates the mean BRT score that was significantly higher ($p < .005$, two-tailed, Bonferroni corrected for multiple comparisons) from the mean baseline score. Error bar indicates ±1 standard deviation. The bar graphs also show (b) the results for all single participants during BRT in different SNRs.

NOV. The brain regions that were significantly differentially activated ($P_{\mathrm{FWE}} < .05$) during the task performance between different noise levels are tabulated in Table 3. A Pearson's correlation analysis was conducted between word-based BRT score obtained for every noise conditions (separately) and fMRI activation (i.e., mean NOV) in twelve ROIs: bilateral STG, HG, SFG, MFG, IFG, and ACC. The purpose of performing this analysis was to determine if there was a possible relationship between behavior and brain activity. From the result, a significant correlation ($p < .05$) was only found between activity of the right SFG and behavioral performance ($r = .404$, $p = .039$) during the BRT in 5-dB SNR.

4. Discussion

The main aim of the present study was to examine the effects of white noise on auditory working memory (AWM) performance in healthy young adults. Specifically, we were interested to see if white noise, at a moderate level, improves AWM performance. Based on the aforementioned studies on stochastic resonance (SR), it has been proposed that adding a moderate level of background noise during a cognitive task would result in the enhancement of performance [7, 8, 9, 10, 11, 12]. At a low level, the noise has insufficient energy to enhance the detection of information by the sensory system [44]. At a high level, noise masks the targeted-speech signal, making it difficult for participants to hear the presented words [45]. Moderate Brain Arousal (MBA) model postulates that the level of intrinsic neural noise affects cognitive performance [14]. The model has also proposed that inattentive individuals and children with attention-deficit hyperactivity disorder (ADHD) have a lower neural noise level than their typically developed peers. Research suggests that white noise has the capacity to alter the signal-to-noise ratio (SNR) and improve performance [8]. SNR is defined as the difference in intensity between the input signal and background noise [46]. Several studies have attempted to determine the optimal SNR that is within the range of enhancement effects. For instance, a study conducted on fifteen healthy young adults showed that behavioral performance on a word-based BRT was significantly enhanced when the task was performed in the presence of 5-dB SNR babble noise as compared to in quiet [10]. In another study conducted on healthy young adults, Angwin et al. [9] demonstrated that white noise has the capacity to enhance learning to stimuli in the visual modality. Helps and colleagues, on the other hand, have explored the beneficial effect of white noise in children with different attentional level [8]. It was found that the presence of white noise improves performance of sub-attentive children but worsened the performance of super-attentive children. The performance of normal-attentive children, however, was unaffected by the presence of white noise. Studies have also shown promising evidence of the use of white noise as a possible therapeutic option for children with ADHD [5, 7, 47]. Although these studies suggested the potential benefits of noise for cognitive performance, definitive conclusions about the effects of white noise on AWM performance in healthy young adults remain ambiguous and demand further investigation. In the present study, we extended this line of

Table 2
Post-hoc test comparing behavioral performance in different signal-to-noise ratio (SNR).

Post-hoc test	SNR (A)	SNR (B)	Mean difference (A-B)	p-value
Tukey's HSD	60-dB SNR	15-dB SNR	-0.70	.551
		10-dB SNR	-3.00*	<.001
		5-dB SNR	-3.90*	<.001
		0-dB SNR	2.65*	<.001

[*] Score that was significantly different from the baseline score ($p < 0.005$; Bonferroni corrected for multiple comparisons).

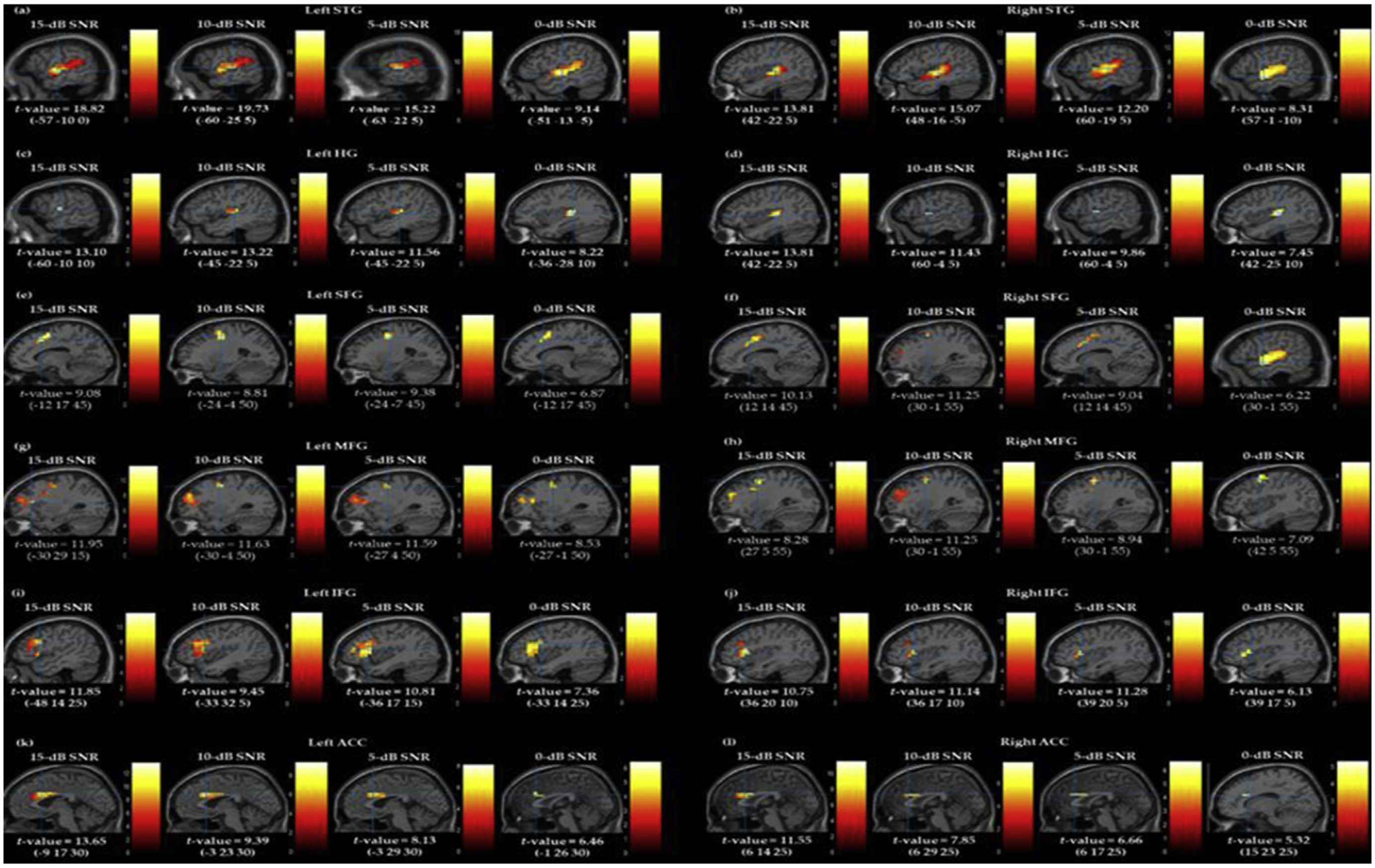

Fig. 4. Statistical parametric maps obtained from second-level random effects analysis ($n = 20$; $P_{\mathrm{FWE}} < .05$) showing brain activation pattern, *t*-value, and peak MNI coordinate (*x*, *y*, *z* in mm) during word-based BRT in different SNR conditions minus baseline in (a) left STG; (b) right STG; (c) left HG; (d) right HG; (e) left SFG; (f) right SFG; (g) left MFG; (h) right MFG; (i) left IFG (j) right IFG (k) left ACC; and (l) right ACC. Brain activations were overlaid onto structural brain images in sagittal slices. The color bar (black to white) indicates the *t*-values for the activated voxel.

research by examining the effects of white noise on AWM performance in healthy young adults.

A word-based backward recall task (BRT) was used to assess AWM performance. The AWM is a cognitive system that maintains and manipulates auditory information in mind [1, 3]. The BRT, rather than a typical word recognition task, was chosen for this study as it requires the participants to store the targeted-speech signal (i.e. maintenance process) temporarily in their mind, mentally rearranged those words in the reverse order of presentations (i.e. manipulation process), and finally to verbally recall the answers. In a word recognition task, on the other hand, participants were usually required to maintain and identify the targeted-word from a given word sequence. The task only involves maintenance of information without a parallel active processing task. Therefore, a word recognition task may not accurately measure the AWM performance. Our first objective was to test the hypothesis that moderate white noise can improve AWM performance through the phenomenon of SR. In this study, we extended previous works by including multiple background noise levels to map out the inverted U-curve for the SR. The noise level used in the present study was within a suitable range that can be used during an extended period of learning. In a systematic review study [48], it has been suggested that the optimal noise level for a classroom ranges from 40 to 65 dB. Our behavioral results in Table 1 indicated that behavioral performance improved gradually from 15 to 5-dB SNR and later decreased at 0-dB SNR, as compared to the quiet (baseline) condition. Post-hoc Tukey's HSD test in Table 2 revealed that performance in 10 and 5-dB SNR was significantly higher than performance in the quiet condition. According to Söderlund et al. [5], SR is quantified by plotting cognitive performance as a function of noise intensity. The plot would appear as an inverted U-curve, where performance increases up to a certain point and decreases afterward. Our result showed a significant quadratic trend for behavioral performance across noise levels [F (4,95) $= 65.32$, $p < .001$], indicating that the pattern of means was curvilinear. Additionally, the interpolation line in Fig. 3(a) exhibited a noise-benefit inverted U-shaped curve for background noise level on the BRT score [12]. Consistent with earlier studies on SR [5, 7, 12, 13, 14], our findings indicated that the effect of noise on performance follows an inverted U-shaped curve. Our result, therefore, supports the hypothesis that moderate white noise can improve AWM performance in healthy young adults via SR mechanism.

Our secondary objective was to understand the underlying mechanism of AWM enhancement. Specifically, we were interested to see how the AWM neural networks respond when performing tasks in the presence of different SNRs. To address this matter, we have used functional magnetic resonance imaging (fMRI) to measure signal changes in blood-oxygen level dependent (BOLD) during task performance. Whole-brain analyses showed significant activation ($P_{\mathrm{FWE}} < 0.05$) in bilateral superior temporal gyrus (STG), Heschl's gyrus (HG), superior frontal gyrus (SFG), middle frontal gyrus (MFG), and inferior frontal gyrus (IFG) across noise levels contrasted against the baseline. Region-of-interest (ROI) analysis was conducted as a further analysis to examine the mean numbers of activated voxels (NOV) in each ROI across noise level. Fig. 5 depicts a quadratic contrast for the NOV across SNRs. The results showed a significant quadratic trend ($p < .05$) in the NOV for the right HG, bilateral SFG, bilateral MFG, bilateral IFG, and right ACC. Similar to that observed for the behavioral data, a significant quadratic trend indicated that the pattern of brain activity (dotted interpolation line) follows an inverted U-shape curve. However, it was not known whether increased activity in the favorable SNRs (i.e., 10 and 5-dB SNR) was associated with

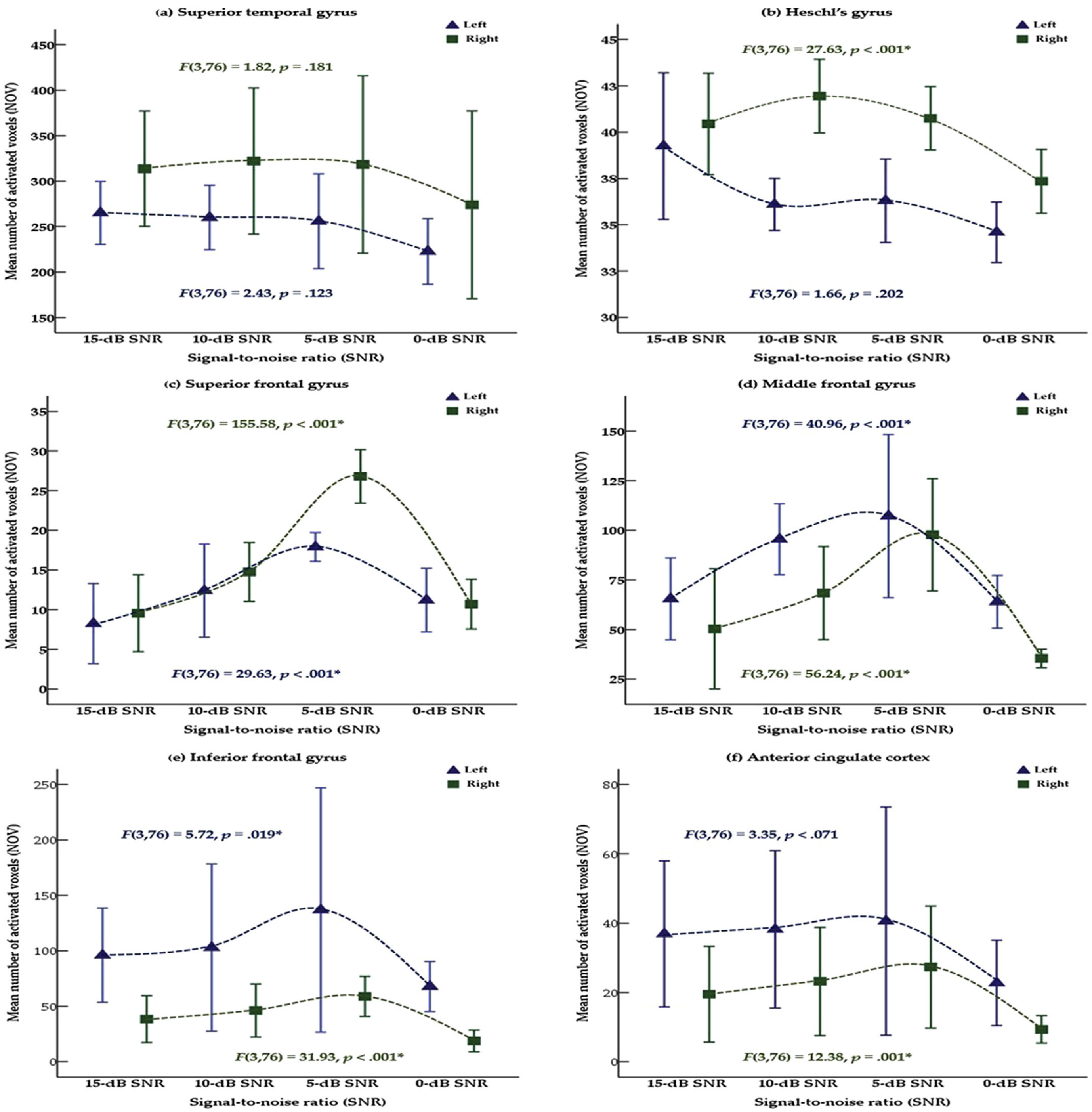

Fig. 5. Mean number of activated voxels (NOV) obtained in bilateral (a) superior temporal gyrus, (b) Heschl's gyrus, (c) superior frontal gyrus, (d) middle frontal gyrus, (e) inferior frontal gyrus, and (f) anterior cingulate cortex is plotted as a function of signal-to-noise ratio (SNR). The dotted interpolation lines indicate the 95% confidence interval of the quadratic polynomial fit through the data points of all conditions. The asterisk mark indicates a significant F-ratio ($p < .05$) for the quadratic trend. The error bars indicate the group ±1 standard deviation around the mean.

increased in performance. Thus, a correlation analysis was conducted to assess for a possible linear relationship between brain activity and behavior performance. Although these regions showed a positive correlation with performance, they were not statistically significant ($p > .05$). A significant positive correlation was only found between the activity of the right SFG and performance ($r = .404$, $p = .039$) when the task was conducted in 5-dB SNR. It has been suggested that the right SFG plays an important role in response inhibition and interference control [49]. Response inhibition is defined as a process by which dominant response is deliberately withheld [50], and that good inhibitory control is associated with improved reasoning ability [51]. From these studies [49, 50, 51], it may be plausible that enhanced performance under favorable SNRs may be attributed to better interference control and reasoning ability. However, taking into consideration that the sample size used in the present study is considered small and that the significance value is near the border, additional research replicating these effects in AWM using a larger sample size is needed to help us clarify this.

Limitations of the present study deserve comment. First, a sample size of 20 participants, these days, may be considered small to draw conclusions of the hypotheses being tested. Although these findings may be valid

Table 3
Contrast, brain region, coordinates of maximum intensity (*x*, *y*, *z* in mm), number of activated voxels (NOV), *t* statistic, and *p*-value obtained from second-level RFX group analysis ($P_{\mathrm{FWE}} < 0.05$).

Contrast (SNR)	Brain region	MNI coordinate	NOV	*t*-value	*p*-value
15-dB > 0-dB	Right claustrum	27 -10 20	7	7.99	.001
	Left claustrum	-24 -19 20	3	7.86	.005
10-dB > 0-dB	Left thalamus	0 -19 5	8	8.08	.001
	Left precentral gyrus	-48 -1 10	4	6.93	.005
	Left postcentral gyrus	-57 -1 15	2	6.81	.012
	Left insular cortex	-30 -37 15	1	6.19	.021
5-dB > 0-dB	Right insular cortex	33 8 20	4	6.64	.007
	Left postcentral gyrus	-24 -31 40	1	6.25	.023

for one study population, it is, however, not justified to extend our conclusions to the general population. Also, to control for the effects of gender, only male participants were recruited in this study. We cannot, therefore, comment on whether the effects of white noise seen here may produce similar outcomes in healthy young adult females. Future work may extend the current research by running a larger sample size including both genders for behavioral testing and to run more trials at the targeted SNR comparisons. Second, the current study was strictly limited by the examination time. Long examination time is undesirable in cognitive studies as participants may become restless and bored, resulting in suboptimal activation towards the end of the fMRI session [34]. There were four experimental runs in this study and each run took 10-minutes to complete. Including the preliminary structural scans and resting duration in between runs, the total fMRI examination time for each participant was approximately 60-minutes. An additional run would have added another 10 min to the experiment. Therefore, to limit the scan duration, the quiet condition was not scanned. Nonetheless, the quiet condition was still performed outside of the scanner to obtain the mean baseline behavioral scores for comparison purposes. The present research may be extended by comparing brain activity during AWM task in quiet and in the favorable SNRs. Another possible improvement to this study could have been in using a longer volume acquisition time (TA) to acquire functional brain volumes. The main reason for selecting a short TA (i.e. 2 seconds) was to reduce the total scan time and reduced scanner noise. As a consequence, we may miss some of the relevant BOLD response. There are increasing numbers of research in the field of silent MRI imaging [52, 53], and hopefully, the next generation of MRI scanners will totally be silent. It has been shown that the nature of the task may potentially influence the effects of white noise on cognitive performance [30]. Therefore, the facilitative effects of white noise seen in this study may not be present in other cognitive tasks. The present research may be extended by expanding the battery of cognitive tasks used. Future work should focus on the implementation of stochastic-white noise in educational settings among healthy students. Implementing white noise during lessons via headphones may be a feasible and cost-effective measure to provide a suitable acoustic learning environment. Future research may also give consideration to the development of applications incorporating ‘adaptive’ stochastic white noise that would adjust the SNR in real-time to always be within the optimal range to enhance performance.

5. Conclusions

This study investigated the effects of white noise on auditory working memory (AWM) performance and examined the underlying neural mechanism of AWM enhancement. We extended previous works by adding multiple noise levels to map out the inverted U-curve as predicted by the SR model. In the present study, we focused on noise levels within the normal communication range, which is suitable for daily use in academic learning. Additionally, our research focused on the auditory modality, as compared to most previous studies in the visual modality. Our results highlighted that the AWM performance was significantly enhanced in 10 and 5-dB SNR. Although the present study is laboratory-based and has a small sample size, it provides an insight into the benefits of white noise on AWM performance and its potential future use in the classroom. In light of these results, we conclude that 10 to 5-dB SNR is within the range of favorable SNRs to improve AWM performance via the mechanism of stochastic resonance. We also proposed that the right superior frontal gyrus (SFG) may be a strategic structure involved in enhancement of AWM performance. However, given that the brain-behavior relationship has a correlation value near the statistical threshold of .05, it is clear that this claim warrants additional research to support or refute such claim. The findings of the present study, nonetheless, add to the very limited literature on the beneficial role of white noise in AWM processing.

Declarations

Author contribution statement

E. Othman: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

A. Yusoff: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

M. Mohamad, H. Abdul Manan, V. Giampietro, A. A. Hamid, M. Dzulkifli, S. Osman, W. I. D. Wan Burhanuddin: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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