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ORIGINAL ARTICLE

# Alpha and Low Gamma Embedded With White Noise Binaural Beats Modulating Working Memory among Malaysian Young Adult: A Preliminary fMRI Study

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## ABSTRACT

**Introduction:** Binaural beats (BB) provisions alpha and gamma have been suggested to modulate working memory (WM), while white noise (WN) acted as a control condition. **Methods:** The current study overlays WN on alpha and gamma tones to study its modulating role on WM performance. A block-design n-back task paradigm used to determine the effect of load on embedded BB on WM performance using functional magnetic resonance imaging. **Results:** Six young adults (3 males and 3 females) with mean age of 23.5 ± 0.84 within the Kota Bharu vicinity participated in the study. A repeated-measures ANOVA ($p<0.05$) on response accuracy indicate medium effect size on condition ($\eta^2 =0.420$), and large effect sizes on groups ($\eta^2 = 0.388$) and load ($\eta^2 = 0.487$). The potential practical difference is more evident on low- (0-back) and high-load (3-back). GWN provision marginally excels, implying its entrainment may benefit WM processing. A repeated-measures ANOVA ($p<0.05$) on reaction time (RT) implied a large effect size on all variables (condition: $\eta^2=0.065$, groups: $\eta^2=0.227$ and load: $\eta^2=0.169$). It was observed that BB exposure elicits a slow processing speed which worsens RT. The neural correlates suggest activated regions in GWN and AWN are associated with attentional mechanisms and WM processes. **Conclusion:** Preliminary findings indicate both embedded BB has a potential to improve WM performance with the cost of slower processing speed. GWN provision modulates attentional mechanisms benefiting WM performance and AWN may enhance performance in extreme ends of WM load.

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**Keywords:** Binaural beats, Auditory, n-back, Working memory, fMRI

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## INTRODUCTION

The concept of binaural beats (BB) was first established by Oster in 1973 (1). In the early 2000s, BB is utilised as a non-invasive intervention to improve cognitive function (2). Binaural beats is generated when two sines of pure tones within a similar range are presented to separate ears (3). For example, exposure of 440 Hz tone to the right ear and 400 Hz to the left ear results in a 40 Hz tone to be perceived. The essential mechanism that modifies brain oscillation in its natural physiological state is neural entrainment (4). Neural entrainment can be achieved by sensory stimulation such as the exposure of BB (5). To date, studies have chosen electroencephalography (EEG) (6–8) and magnetoencephalography (MEG) (9) with the neural correlates of BB exposure requires further exploration.

Working memory (WM) requires sustained attention to encode information and it has been postulated that noise interferes with one's concentration on a task as it splits the attentional resources between noise and useful information at hand (10). The neural activation associated with verbal WM has been found to be influenced by reaction time (RT) and load (11). Memory processes are dependent on the smooth interaction between different brain regions and brain oscillation is the glue that facilitates its processes (5). The alpha timescales range from 8-12 Hz and gamma exceeds 30 Hz (4). The alpha range emerges during attention and increasing memory demands (12) and suggests inhibiting cortical areas (13). The increment in the alpha neural oscillation increases with higher WM (14,15). Currently, the studies involving alpha BB were inconclusive in its findings (16,17).

The exposure to low gamma range (30-60 Hz) BB, on the other hand, have been associated with improvement in attentional focus (9,18). In relation to WM performance, (8,19) did not find any significant improvement. White noise (WN) in BB studies have been implicated as a neutral stimulus when comparing the efficacy of BB (19,20). Notably, WN provision has previously been found to improve the attentional capacity of children with attention deficit hyperactivity disorder (ADHD) (21).

The utilisation of binaural beats in modulating WM has increased over the years and it can be observed that the gamma and alpha binaural beats have provided inconsistent findings in the past (8,16,19). The provision of WN has been found to be detrimental to those with normal cognitive ability and as of BB studies, it has often been used as a control condition.. The current study aims to identify the WM performance by masking white noise on alpha BB and gamma BB, creating alpha embedded with white noise (AWN) and gamma embedded with white noise (GWN). With the utilisation of fMRI and sparse temporal paradigm, the neural correlates of the succeeding task post-BB exposure were explored. The chosen WM task, the n-back task is selected based on the recommendation of Kirk et al., (22) to provide a load-dependent WM task in the future for better generalisation of BB's modulation. The n-back task requires both attentional and WM mechanism as the lowest load (i.e. 0-back) has been considered as an attentional load (23).

## MATERIALS AND METHODS

### Participants

A total of six participants (three males and three females, mean age = 23.5 ± 0.84 were recruited from the attending students and employees from the 1) Universiti Sains Malaysia, Health Campus and 2) Hospital Universiti Sains Malaysia, Kubang Kerian, Kelantan. The inclusion criteria were healthy Malaysian young adults with normal hearing as measured by hearWHO app, should not be on medications or caffeine prior to the experiment with no known neurological disease and no implants incompatible with MR-scanning. The study was approved by USM Ethics Committee: USM/JEPeM/20060308, in compliance with the Declaration of Helsinki.

### Experimental task and data collection procedure

The presentation of n-back task requires the participants to maintain target stimulus and to continually update the currently held stimuli. Participants are required to hold on to current information in the WM while consistently manipulating and updating it.

The participants' WM performance using n-back task with three different loads (0-, 1- and 3-back) was obtained pre and post alpha embedded in white noise (AWN) and gamma embedded in white noise (GWN) exposure. Followed by pink noise (PN) exposure which was suggested to induce a reduction in brain wave complexity by allowing slow rhythm oscillation driving a slow-wave activity beneficial to memory consolidation in humans (24). It has been suggested that an estimated exposure of 1 minute of PN is sufficient to produce the desired effect (25). Participants were exposed to either AWN or GWN on a separate day. Participants were given a different auditory condition from the first session, followed by a different set of n-back task and pink noise provision.

The visual n-back task was presented using E-Prime 1.0. Three levels of n-back task (0-back as low load task, 1-back as medium load task, and 3-back as high load task) were provided (26). Each stimulus block contained active n-back tasks and distractors, presented in a pseudo-random order. At the start of each block, instruction was provided and shown for 6s. A slide stating the trial condition was presented for 0.5 second (s), followed by the presentation of fixation point for a duration of 0.5s. The stimuli slide was presented in 2.5s, followed by a fixation point. Each active n-back task block includes five slides of letters, equating to 14.5s of active task.

Each block includes 216 slides and participants responded to the stimulus either by a right index finger or middle finger button press whether the current slide did or did not match the presented n-trials. Each block consists of two match trials of each load, equating to six match trials per run. Thus, 18 match trials of 0-back, 1-back and 3-back task over three runs. A rest block of 10 seconds was designated between each block of n-back task. The paradigm can be found in Figure 1.

Different sets of n-back tasks with different targets were given to the participants during the baseline, after AWN

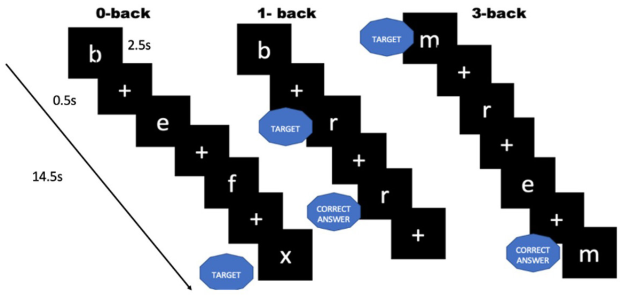

**Figure 1: The n-back paradigm schematic.** Each run contained 3 blocks with 3 trials of each load in every block. Each block includes 216 slides (0.5 seconds of trial condition slide + 0.5 seconds of fixation point + 2.5 seconds of stimulus presentation ). A trial condition slide was presented to the participants prior followed by the task stimuli.

and after GWN condition to compare their performance and the relevant neural correlations before and after the auditory exposure. Studies in the past have chosen EEG and MEG as a modality to study BB cortical entrainment. However, none have used an additional PN provision to reduce the cognitive complexity caused by the BB exposure and the WM task.

**Auditory stimulus**

The BB used in the experiment was created using Audacity® software, version 2.3.3 (available at https://www.audacityteam.org) and controlled using E-Prime 1.0. Wired headphones with separate channels was used to present the sound. The auditory volume adjusted to a comfortable level of 75db (27).

The frequencies involved for the BB were replicated from a previous study conducted by Kraus (16), 230 and 220.45 Hz, creating a perceived frequency of 9.55 Hz. The selected gamma wave was 40 Hz; 440 Hz and 480 Hz based on Engelbregt et al. (19). The auditory stimulus is embedded utilising WN generated in the aforementioned software. The PN is created using an existing sound on the Audacity software. Sparse temporal paradigm was used to administer both auditory stimuli and PN to minimise the interference of loud scanner noise during scan acquisition (27).

The auditory stimulus exposure was presented on a different day from the baseline collection in two separate sessions. It was single-blinded provisioned and the order of presentation has been established prior to the experiment. Participants were presented with either 15 minutes of alpha embedded with white noise (AWN) or gamma embedded with white noise (GWN) in the first session, conducted in the morning. The selected auditory stimulus, i.e., GWN AWN were given to the participants in 32 seconds stimuli burst with sparse delays of 8 seconds as suggested by Behler and Uppenkamp (2020). The participants were only exposed to 1 minute of PN as recommended by Seifi Ala et al.(2018). The sparse temporal sampling design is shown in Figure 2.

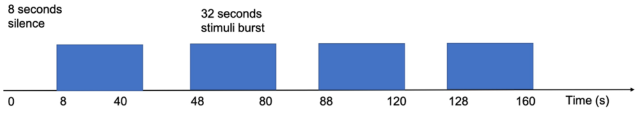

**Figure 2: The sparse temporal paradigm.** The BB stimuli is presented for a duration of 32 seconds following an 8 seconds silence.

**fMRI protocol**

The functional and anatomical images were performed using a 3.0 Tesla Philips Achieva scanner (Philips, Best, The Netherlands) equipped with 8-channel head coil at the Department of Radiology of Hospital Universiti Sains Malaysia. The auditory stimuli were presented via a compatible fMRI/MRI headset.

The high-resolution anatomical images were acquired using the following parameters: TR 7500ms, TE 35ms, voxel matrix 228 x 227 voxel matrix, and an in-plane resolution of 1.1 mm x 1.1 mm x 1.2 mm. The structural image was obtained for co-registration, normalization, and assurance of structural normality upon the functional session. The functional images collected (for n-back task) in one session were acquired with an imaging area consisting of 40 oblique axial slices with the following parameters: TR 2000ms, TE, 20ms, flip angle 78 °, voxel matrix 68 x 73, field of view 20 cm, slice thickness 3.0 mm, in-plane resolution 3.03 mm x 3.01 mm x 3.0 mm. The sparse temporal sampling paradigm was adapted during the exposure to AWN, GWN and PN with varying duration. Both AWN and GWN were exposed to participants within 15 minutes, separated into 32 seconds of stimuli burst and 8 seconds silence. The participants were only exposed to 1 minute of PN. A TR of 8000 ms was utilised with TE 20 ms, flip angle 78 °, voxel matrix 68 x 73, field of view 20 cm, slice thickness 3.0 mm, in-plane resolution 3.03 mm x 3.01 mm x 3.0 mm for all auditory conditions.

The gathered fMRI data were analysed using the latest version (12) of Statistical Parametric Mapping (SPM12) analysis package (Wellcome Department of Cognitive Neurology, London, UK; Friston et al., 1994). The following pre-processing pipeline was adhered to for each subject; motion correction, slice timing, co-registration, normalisation and smoothing (6 mm FWHM) (28).

**Behavioural analysis**

The initial data behavioural analysis was performed using SPSS Version 26 (IBM). Response accuracy and reaction time (RT) for correct responses were calculated as behavioural measurements. Reaction time is the time taken by the subject to respond during the trials. Based on Jacola et al. (2004) (29), the calculation of the response accuracy is derived using the following formula: Accuracy = Hits + Correct Rejections/ Total Stimuli. Hits refer to the number of targets minus omission errors (misses) and correct rejections. The correct rejections equal the number of commission errors (false alarms) subtracted from the distractors.

A parametric two-way repeated-measures ANOVA was undertaken as the behavioural data did not violate the normality assumption with despite the small sample size. The Shapiro-Wilk test for normality indicate the p-value of variables is greater than 0.05, the sphericity however was violated as the Mauchly's test of sphericity was more than 0.05 for condition* load in response accuracy, thus a Greenhouse-Geisser corrected results were reported for both RT and response accuracy.

The investigation was conducted to assess the working memory performance between each auditory condition, on each behavioural measure (AWN and GWN) between-subject factor of auditory condition (baseline, AWN and GWN) and the within-subject factor of n-back task (0-, 1- and 3- back). The multiple comparison analysis was conducted at $p<0.05$. The resulting effect size of the main and interaction effect were interpreted based on the partial eta squared rule of thumb by Cohen (1988) (30). According to the rule of thumb small $\eta^2$ = (0.01 to 0.05), a range of 0.06 to 0.13 is a medium effect and a large effect size is categorised as ($\eta^2 > 0.14$).

### Imaging analyses

Fixed-effects (FFX) approach has been used to understand signal changes by accounting for the variance only within individuals. The brain activation results were visualised using MRIcron (Chris Rorden, v1.0.20190902, 2 September 2019, http://people.cas.sc.edu/rorden/mricron/index.html).

### Fixed-effects analysis (FFX) for n-back load (baseline, post-AWN, post-GWN)

The fMRI data were analysed using FFX for each n-back load on each condition; baseline, post-AWN and post-GWN respectively. The FFX analysis was completed to determine the group level activation of each n-back load (0- ,1- and 3-back) during baseline, post-AWN and post GWN with varying loads. The variables were thresholded at uncorrected $p<0.05$ with the extent threshold of 20 voxels.

## RESULTS

### Behavioral Result

#### *Reaction Time (RT)*

A repeated-measures ANOVA was conducted that examined the effect of condition (pre and post) and BB (AWN and GWN) on n-loads (0-, 1- and 3-back) in RT on healthy participants. The main effect of the condition indicated no significant differences (F (1,5) = 3.622, p = 0.115). However, the effect size value ($\eta^2$= 0.420) suggested a large practical difference between conditions. Descriptive statistics showed that mean RT were slightly slower for post (M = 649.80) compared to pre (M = 563.96) exposure to BB. The finding proposed that brief exposure to AWN and GWN potentially deteriorate processing speed in n-back task. Main effect of BB showed no significant differences on RT between AWN and GWN (F (1,5) =3.163, p =.135). The effect size estimates indicated large effect size ($\eta^2$=.388) between AWN and GWN.

The finding suggests participants have a potential to perform uniquely in AWN (M = 611.37) and GWN (M = 602.40). There are no significant differences between varying working memory loads on the RT (F (2,10) = 4.742, p = 0.051), but the effect size value ($\eta^2$ =0.487) implies large practical differences. The finding proposed that participants take longer RT to respond at higher load (3-back; M = 647.31) than 1-back (M=608.07) and 0-back (M = 565.30).

The interaction effects are not present for 1) condition and BB (F (1,5) = 3.163, p = 0.135, $\eta^2$ = 0.388), 2) condition and load (F (2,10) = 0.904, p = 0.409, $\eta^2$ = 0.153), 3) BB and load (F (2,10) = 2.009, p = 0.200, $\eta^2$ = 0.287), and 4) condition, BB and load (F (2,10) = 2.009, p = 0.200, $\eta^2$ = 0.287). However, all interaction effects provided a large effect size between the variable pairs on the RT. The results suggested that all variable pairs on RT have practical differences. Comparison in descriptive statistics indicated slightly higher mean RT was taken during the highest load (3-back; AWN: MPre-AWN: 600.51 and MPost-AWN: 693.29; GWN: MPre-GWN: 600.51 and MPost-GWN: 694.94) in post-BB exposure than moderate (1-back; AWN: MPre-AWN: 581.73 and MPost-AWN: 660.60; GWN: MPre-GWN: 581.73 and MPost-GWN: 608.23) and low load (0-back; AWN: MPre-AWN: 509.65 and MPost-AWN: 622.44; GWN: MPre-GWN: 509.65 and MPost-GWN: 619.31) for both BB.

Results showed that WM load has a relationship with RT, whereby higher WM demand requires longer processing speed. Additionally, slow processing speed was shown in AWN and GWN, consistent with previous findings in pure gamma and alpha (7,8,19) BBs. Gamma and alpha BBs embedded with white noise can be anticipated to change the processing speed contrarily in distinct WM load. Comparison on RT in post-exposure BBs indicated that AWN and GWN perform similarly for higher (3-back) and low (0-back) WM load, but slightly faster processing speed in GWN than AWN for moderate WM load (1-back). It can be proposed that GWN entrainment performed slightly better than AWN in processing memory and cognition especially in moderate WM load.

#### *Response Accuracy*

A repeated measures ANOVA examined the effect of condition (pre and post) and BB (AWN and GWN) on n-loads (0-, 1- and 3-back) in the accuracy of healthy participants. Findings indicated no significant differences in the main effect of condition (F (1,5) = 0.350, p = 0.580, $\eta^2$ = 0.065), but the effect size value indicated has a medium practical differences.

The main effect of BB showed no significant differences (F (1,5) = 1.467, p = 0.280, $\eta^2$ = 0.227). A large effect size was however observed. From this finding, it can be suggested that the accuracy scores for AWN (M = 0.105) and GWN (M = 0.109) have the potential to be practical differences. The main effect of WM load indicated no significant differences (F (2,10) =1.019, p= 0.372 $\eta^2$ =0.169), but the effect size estimate showed large practical differences. Descriptive statistics showed slight changes in accuracy for 0-back (M = 0.093), 1-back (M = 0.121) and 3-back (M = 0.107). It can be postulated that accuracy score is associated with WM load, different working memory load requires different cognitive demand and fluid intelligence as implied in differing accuracy score.

The interaction effects are not present for 1) condition and BB (F (1,5) = 1.467, p = 0.280, $\eta^2$=.227), 2) condition and load (F (2,10) = 1.070, p =.352, $\eta^2$ = 0.176), 3) BB and load (F (2,10) = 0.802, p = 0.458, $\eta^2$ = 0.138) and 4) condition, BB and load (2,10) = 0.802, p = 0.458, $\eta^2$= 0.138). Large effect sizes were observed for each pair, as all interaction effects indicate potential practical differences. The comparison in descriptive statistics indicated slightly higher mean accuracy was shown during 3-back (AWN: MPre-AWN: 0.094 and MPost-AWN: 0.109; GWN: MPre-GWN: 0.094 and MPost-GWN: 0.130) and 0-back (AWN: MPre-AWN: 0.074 and MPost-AWN: 0.107; GWN: MPre-GWN: 0.074 and MPost-GWN: 0.111) for both BB, but differ for 1-back (AWN: MPre-AWN: 0.131 and MPost-AWN: 0.107; GWN: MPre-GWN: 0.131 and MPost-GWN: 0.113).

Inconsistent changes in accuracy at different working memory load is proposed due to differing working memory demand requirement. Comparison on accuracy in post-exposure BBs indicated that AWN and GWN perform similarly in different WM load. Interestingly, findings showed that BB has a potential to improve accuracy score at higher and low WM (3- and 0-back).

### Whole-Brain Activation

A fixed-effects analysis (FFX) was conducted to examine the effect of condition (baseline, post-AWN and post-GWN) on n-loads in the brain activation of healthy participants. Findings indicated different brain regions are activated in each condition and WM load. Findings showed that the recruitment of brain regions stipulated in the attentional mechanism were found in the brain activation map post-GWN and the activation of WM associated areas were evident in post-AWN.

### Comparison on 3-back>1-back WM load in varying conditions (baseline, post-AWN, post-GWN)

#### *Baseline*

The brain activation in 3-back>1-back contrast shows the recruitment of the bilateral precentral gyrus (PCG) and right postcentral gyrus (PoCG). Other notable regions include the left pars triangularis, left cerebellum and right middle occipital gyrus (MOG).

#### *Alpha embedded with white noise*

The brain regions in 3-back>1-back 1 contrast recruited after the exposure to AWN is more compared to the baseline condition. Regions involved are the bilateral superior frontal gyrus (SFG), left middle frontal gyrus (MFG) and left frontal pole.

#### *Gamma embedded with white noise*

In the GWN condition, only the recruitment of right anterior cingulate gyrus and left superior temporal gyrus (STG) were found.

The difference between the brain activation in baseline and post-BB during 3-back>1-back contrast can be observed in Figure 3.

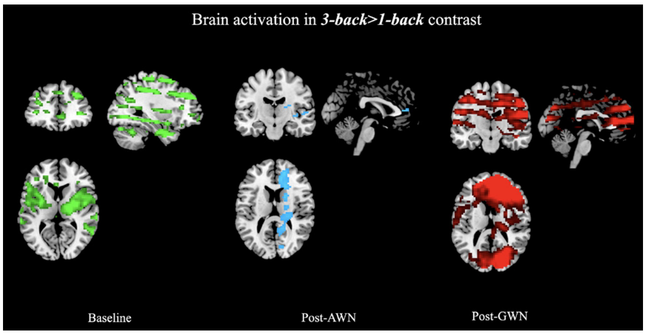

**Figure 3: Brain activation in 3-back>1-back contrast** thresholded at an uncorrected p<0.05, extent threshold =20. The activation found in post-GWN includes a larger bilateral area of the brain including fronto-parietal areas. Whilst post-AWN is focused on the left hemisphere with a pronounced activation of frontal areas along with left cingulum.

### Comparison on 3-back>0-back WM load in varying conditions (baseline, post-AWN, post-GWN)

#### *Baseline*

In the 3-back>0-back contrast, brain regions which are activated encompasses the bilateral activation of SFG and MFG. The recruitment of the left cerebellum is also evident, followed by the recruitment left supramarginal gyrus (SMG), left medial SFG, left lingual gyrus, right putamen and right occipital fusiform gyrus.

#### *Alpha embedded with white noise*

Post-AWN brain map of 3-back>0-back contrast consist of the parietal regions such as right cuneus, left SMG, and left angular gyrus. The recruitment of subcortical region such as right putamen and corpus callosum were also exhibited. In addition, only the right SFG was activated in the frontal region as well as left MOG in the occipital region.

#### *Gamma embedded with white noise*

The recruitment of parietal regions are evident in the post-GWN map with the activation of bilateral PCG, left supplementary motor cortex (SMC) and left angular gyrus. Other notable regions include BA13 (insula), the right superior occipital gyrus (SOG) and the left thalamus. The brain activation evidently differ in both post-BB condition in lower load as shown in Figure 4 and 5.

### Comparison on 1-back>0-back WM load in varying conditions (baseline, post-AWN, post-GWN)

#### *Baseline*

On the 1-back>0-back contrast, parieto-orbital regions are recruited heavily such as the bilateral activation of

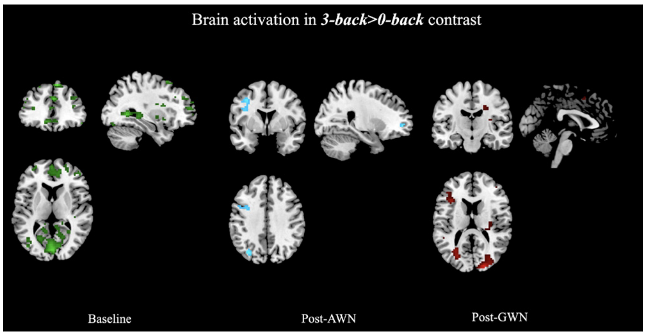

**Figure 4: Brain activation of 3-back>0-back contrast in three different conditions** (puncorrected <0.05, extent threshold = 20). The recruitment of regions post-GWN indicates its association with the attentional mechanism and post-AWN map shows the activation associated with WM mechanism. Notably, lesser brain regions are activated in post-BB condition compared to baseline.

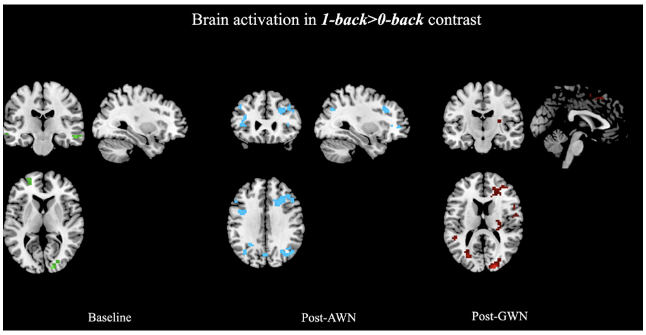

**Figure 5: Whole brain activation of 1-back>0-back contrast in three different conditions** thresholded at an uncorrected p<0.05, extent threshold =20. Post-BB conditions (AWN and GWN) exhibits larger fronto-parietal activation compared to during baseline.

the posterior orbital gyrus, PCG left occipital fusiform gyrus, right inferior occipital gyrus, right cuneus, right precuneus and right angular gyrus. The activation of regions such as the left ventral DC, caudate nucleus and brain stem were also evident. In addition, the frontotemporal such as bilateral MTG, left MFG, right SFG and the left middle cingulate gyrus.

### *Alpha embedded with white noise*

In the 1-back>0-back contrast, it is found that more parietal regions are activated; left SMG, left SPL, left angular gyrus and right precuneus. Other regions that were recruited includes the right putamen, right posterior cingulate gyrus and right SOG.

### *Gamma embedded with white noise*

The recruitment of left SMG was also found in 1-back>0-back contrast post-GWN. Other parietal regions such as left PCG, left SMC, left precuneus and right cuneus were evident. Regions such as right MFG and right planum polare were also activated.

Results showed that WM task with higher load demands larger recruitment of associated attentional and WM processing compared to moderate and low WM load. A summary of the comparison of load activation in both AWN and GWN can be found in Table I.

Dominantly, parietal regions are recruited in post-BB conditions as compared to baseline condition (see Table I) in lower loads. The recruitment of frontal regions are found in higher loads post-AWN. Meanwhile post-GWN exposure activates more parietal regions. The involvement of the fronto-parietal-occipital region for AWN and GWN in various WM loads is suggested to be associated with different WM processing stages, including executive control and visual processing.

## DISCUSSION

The current findings showed AWN and GWN induced slow reaction time but slightly improved response accuracy, especially on low (0-back) and high-load (3-back). In addition, GWN marginally transcends AWN in the n-back task for the behavioural results. The GWN condition activates more parietal regions. Meanwhile activation post-AWN recruits frontal regions in higher load and parietal regions in lower load.

The main effect of condition, groups and load in post-BB exposure indicated a non-significant finding. However, the effect size value of the variables suggests large practical differences. The mean RT were found to be slightly slower in post-BB condition as compared to pre-BB condition especially post-AWN condition. Despite no observed interaction effect in all variables, a large effect size was observed between the variable pairs. Consistent with previous findings on pure tone BB (6,8,16,19), longer RT was seen at a higher load (3-back) as compared to 1-and 0-back in the post-BB condition. This indicates that higher WM load influences the processing speed, thus the longer RT. A slightly better processing speed is seen in post-GWN condition in moderate load (1-back), suggesting that GWN entrainment allows slightly faster memory and cognitive processing in moderate WM load.

The conducted statistical analysis shows no main effect of condition, groups and load in post-BB exposure on response accuracy. However, similar to the effect size value of RT, a medium and large effect size was observed in the main effect and interaction effect of the variables. The accuracy in post-BB were found to have inconsistent changes. Although both AWN and GWN performed similarly, it should be noted that the findings point to the potential of BB in improving accuracy scores at a lower and higher WM load (0- and 3-back). The study findings contradict the previous studies (6,8,16,19) on pure tone alpha and gamma which suggest the likelihood of BB embedded with WN may have elicited better response accuracy through increased distractor inhibition.

fMRI analysis using FFX indicate that both BBs deviate

**Table I: Whole brain activation of n-back load (0-, 1- and 3-back) in different conditions (baseline, post-GWN, post-AWN) ( $p^{uncorrected} < 0.05$, extent threshold = 20)**

| Condition | N-back load | Activation Cluster | Cluster extent (voxels) | Maximum T-value | Peak MNI coordinates | | |
|---|---|---|---|---|---|---|---|
| | | | | | X | Y | Z |
| **Baseline** | *3-back> 1-back* | Right precentral gyrus | 1084 | 8.86 | 17 | -28 | 65 |
| | | Left cerebellum | 228 | 7.62 | -37 | -70 | -25 |
| | | Left postcentral gyrus | 24 | 5.91 | -58 | -10 | 26 |
| | | Left precentral gyrus | 361 | 4.55 | -52 | -4 | 11 |
| | | Left pars triangularis | 35 | 3.83 | -37 | 38 | 5 |
| | | Right MOG | 20 | 2.45 | -1 | 48 | -13 |
| | *3-back> 0-back* | Right SFG | 79 | 4.52 | 63 | -1 | -13 |
| | | Left MTG | 1083 | 4.08 | -55 | -67 | 2 |
| | | Left SMG | 115 | 3.94 | -55 | -46 | 41 |
| | | Left SFG | 96 | 3.89 | -16 | 54 | 32 |
| | | Left cerebellum | 51 | 3.81 | -25 | -82 | -34 |
| | | Right MFG | 179 | 3.66 | 2 | 38 | 29 |
| | | Left MSFG | 313 | 3.61 | -4 | 60 | 5 |
| | | Right MTG | 57 | 3.45 | 66 | -25 | -10 |
| | | Right putamen | 49 | 3.42 | 23 | 8 | -7 |
| | | Left lingual gyrus | 87 | 2.92 | -13 | -79 | -13 |
| | | Right occipital fusiform gyrus | 60 | 2.78 | 23 | -82 | -16 |
| | *1-back> 0-back* | Left MFG | 287 | 4.14 | -28 | 54 | -1 |
| | | Right cuneus | 87 | 3.91 | 17 | -94 | 8 |
| | | Right posterior orbital | 44 | 3.9 | 23 | 23 | 22 |
| | | Left posterior orbital | 153 | 3.81 | -34 | 26 | -19 |
| | | Left MTG | 52 | 3.76 | 36 | -55 | 53 |
| | | Right SFG | 285 | 3.72 | -43 | 14 | 44 |
| | | Right frontal supp | 1012 | 3.62 | 20 | 32 | 44 |
| | | Left precentral gyrus | 123 | 3.54 | 57 | -22 | -16 |
| | | Right angular gyrus | 122 | 3.52 | -37 | -19 | 50 |
| | | Right precuneus | 70 | 3.48 | 48 | -67 | 35 |
| | | Left occipital fusiform gyrus | 486 | 3.37 | 2 | -70 | 44 |
| | | Left middle cingulate | 56 | 3.17 | -43 | 20 | -34 |
| | | Left caudate | 133 | 3.08 | -4 | 20 | 29 |
| | | Right IOG | 56 | 3.04 | -10 | 14 | 5 |
| | | Right MTG | 73 | 3.03 | 42 | -67 | -1 |
| | | Right precentral BA3 | 93 | 2.84 | 42 | -25 | 59 |
| | | Left ventral DC | 43 | 2.83 | -16 | -22 | -16 |
| | | Brain stem | 90 | 2.5 | 17 | -25 | -10 |
| **Post- AWN** | *3-back> 1-back* | Left frontal pole | 484 | 4.32 | -4 | 66 | 11 |
| | | Right SFG | 248 | 3.42 | 20 | 48 | 44 |
| | | Left MFG | 32 | 3.26 | -28 | 23 | 44 |
| | | Left SFG | 33 | 3.08 | -25 | 38 | 44 |
| | | Left cingulum (BA24) | 25 | 2.64 | -13 | 2 | 41 |
| | *3-back> 0-back* | Left MOG | 65 | 3.98 | -34 | -70 | 35 |
| | | Right cuneus | 31 | 3.85 | 11 | -91 | 23 |
| | | Left SMG | 32 | 3.63 | -52 | -52 | 26 |
| | | BA40/Left angular | 31 | 3.12 | -43 | -49 | 47 |
| | | Right putamen | 46 | 2.5 | 30 | 8 | -1 |
| | | Corpus callous | 20 | 2.49 | 6 | -37 | 20 |
| | | Left SFG | 26 | 2.48 | -19 | 57 | 2 |
| | *1-back> 0-back* | Left SMG | 275 | 4.98 | -52 | -52 | 26 |
| | | Right SOG | 78 | 4.16 | 14 | -91 | 23 |
| | | Left SPL | 48 | 3.26 | -10 | -70 | 53 |
| | | Left precuneus | 63 | 3.22 | -10 | -73 | 35 |
| | | Right Putamen | 156 | 3.16 | 23 | -7 | 8 |
| | | Right angular | 43 | 3.1 | 39 | -58 | 32 |
| | | Right PCg | 46 | 2.6 | -5 | -40 | 23 |
| **Post-GWN** | *3-back> 1-back* | Right ACC | 16648 | 16.65 | 11 | 42 | -7 |
| | | Left STG | 115 | 9.88 | -49 | 2 | -13 |
| | *3-back> 0-back* | Right SOG | 190 | 5.32 | 23 | -94 | 11 |
| | | Left PCG | 227 | 4.18 | -40 | -1 | 26 |
| | | Left Angular gyrus | 94 | 3.39 | -28 | -70 | 38 |
| | | BA13/insula | 51 | 3.32 | -49 | -46 | 20 |
| | | Left SMC | 39 | 2.8 | -7 | 8 | 47 |
| | | Right PCG | 21 | 2.4 | 57 | -7 | 29 |
| | | Left thalamus | 20 | 2.22 | 20 | -22 | 5 |
| | *1-back> 0-back* | Right cuneus | 144 | 4.24 | 20 | -91 | 11 |
| | | Left SMG (BA13) | 52 | 3.37 | -46 | -43 | 17 |
| | | Right MFG | 104 | 3.29 | 39 | 51 | 20 |
| | | Left SMC | 105 | 3.24 | -7 | -1 | 56 |
| | | Left precuneus | 29 | 2.8 | -10 | -76 | 41 |
| | | Left PCG | 139 | 3.2 | -43 | -4 | 35 |
| | | Right planum polare | 40 | 2.61 | 45 | 2 | -13 |

Abbreviation:
BA: Brodmann's area; SMG: supramarginal gyrus; SOG: superior occipital gyrus; PCG: precentral gyrus; SFG: superior frontal gyrus; PoCG: postcentral gyrus; MFG: middle frontal gyrus; MOG: middle occipital gyrus; ACC: anterior cingulate cortex; STG:superior temporal gyrus; SMC: supplementary motor cortex; PCg: posterior cingulate gyrus; MTG: middle temporal gyrus; SPL: superior parietal lobule

in their brain activations. Post-AWN exhibits more recruitment of the fronto-occipital regions whilst post-GWN activates more parietal regions.

Based on Zhao et al. (2017)(23), the alpha neural oscillation is linked to SFG, MFG and MTG which are consistent with the findings of this current study. The activation has been postulated to be associated with maintenance and stronger distractor inhibition. Additionally, AWN showed larger recruitment in the occipital regions such as right SOG and left MOG , which is recommended due to visual association processing such as registering properties of visual information like orientation and colour (31). It has been proposed that SOG benefits the higher-order cognitive processes by processing visual memory (31). Larger recruitment of occipital regions is observed in the low load (0-back) compared to other n-load (see Table 1). The exposure of AWN provides evidence that low load may be centered on visuospatial processing rather than maintaining the attentional load.

Cappell et al. (32) suggested that increase activation in the prefrontal cortex is necessary to cater to different WM load demands. In contrast, Arsalidou et al. (33) indicated that prefrontal cortex activation fluctuates during a medium load condition. These are contrary to the current findings in 3>1-back post-AWN (see Table 1), whereby frontal regions were observed such as bilateral SFG and left MFG. Thus, it can be suggested that the exposure to alpha embedded with white noise may have worsened the performance of those with normal attention as they have reached the optimal level of neural noise (34), especially if the recruited participants are healthy young adults. Furthermore, alpha neural oscillation has been postulated to demonstrate a stepwise change and the occurrence of saturation effect during load based tasks (35,36). The aforementioned studies have shown a stagnation of alpha oscillation after the medium load, i.e., at 6- and 8-items conditions than low to medium load.

The parietal region activation is suggested to be associated with manipulating retained information that refers to attentional mechanism and temporarily storing information (10). Post- AWN condition was found to recruit the left SPL, part of the working memory component. The aforementioned region was found to be a necessary factor in improving response accuracy, its activation may have assisted participants task performance in the lower load (37).

The role of gamma has been linked to attention-modulation (9,18) and the improvement of the response accuracy of the participants may be attributed to the enhanced attention. Attention differentiates short-term memory and working memory to ensure the information is stored in the long-term memory. Surqvist et al.(38) suggested that higher cognitive exposure is adequate to shield against distraction, evidently improving performance after the GWN exposure.

The recruitment of the regions involved in both effortful attention and working memory processes including the MFG, insula and the cingulate, were found after GWN exposure during n-back task. The engagement of the ACC is associated with task load and increasing task difficulty (39). Further, the activation of the right hemisphere indicates that GWN aids in updating action in instances of distraction (38). Additionally, the activation of the bilateral thalamus was found during the 3-back>0-back contrast upon exposure to GWN. The GWN oscillation that maintains the thalamocortical interaction (40) can be suggested to have helped coordinate processing from the senses and the cortical sources (33). Thus, GWN plays a role in maintaining communication between the thalamus and the cerebral cortex, which further aids information processing (40). Thalamus involvement is also likely to aid the task performance in higher load, as observed with the improved response accuracy after GWN exposure (33). However, it is beyond the scope of the current study to understand the interaction or the functional connectivity of the BB neural processing.

Larger activation in the parietal areas were found after exposure to GWN (see Table 1). This finding corroborates with Clark et al. (41), in which the attentional control required in WM task has also been reduced and likely has mimicked the approach of an individual with better cognitive ability. Additionally, the recruitment of parietal areas could be attributed to the training effect (41), as the participants have been exposed to the n-back task prior to both sessions, although participants were given different sets of n-back tasks. The influence of the BB exposure has likely modulated the inhibition of non-associated WM regions by influencing the executive function areas.

Notably, the activation of the right planum polare in 1-back>0-back post-GWN contrast exhibits that BB projection may differ from the normal auditory information. Commonly, it is transmitted from the medial geniculate nucleus in the thalamus to the primary auditory cortex (A1), the Heschl's gyrus (42). It is, however, beyond the scope of the current study to understand the interaction or the functional connectivity of the BB neural processing.

In the current methodology, the participants were exposed to each BB condition within a 1 to 2 hours gap, which may have successfully reduced the carryover effect of entrainment of one BB to another. On the other hand, the residue of one condition may have been brought forth to another condition. Thus, it is likely that the improvement of the response accuracy in GWN can be attributed to the carryover effect of AWN entrainment if participants were exposed to AWN earlier. However, we were unable to ascertain whether entrainment occurred in the first place, as a previous review by Obleser and Kayser (4) observed that entrainment on the oscillatory process caused by external sensory stimuli is debatable. Further, there is the question of how long the entrainment of BB has lasted and whether the residues of one BB was carried over regardless of the gap provided between the exposures. Therefore, further study is needed to answer these questions.

A burst of sounds instead of continuous binaural beats exposure is considered more beneficial (43). The current study undertook a sparse temporal sampling paradigm that allows 32 seconds of sound and 8 seconds of silence to be exposed to the participants accumulating to 15 minutes of exposure of each BB. The administration of burst of sounds as opposed to continuous exposure commonly used in the field (8,16,19) may have improved the findings in terms of response accuracy of the WM task after GWN exposure. Even so, the recommended duration provision of BB has remained unanswered and has plagued previous studies (7–9,16,19). In the current study, it was found that there are no significant differences between the baseline and after AWN or GWN exposure suggesting the modulatory role of BB has been limited. Hence, a comparison between the varying duration and whether a peak performance can be derived from the exposure of each BB may provide further information on the suggested duration of BB. Further, the possibility of longer duration or a longitudinal study requiring weekly or daily exposure would provide a clearer picture of its modulatory role. The lack of significant findings may be due to the low statistical power contributed by the small sample size of 6 participants. Nevertheless, the effect sizes present in the behavioural findings suggest a slight improvement upon the exposure to BB. A sample size of 20 has been suggested may be sufficient to provide 80% power with an alpha level of 0.001 (44) to make generalisations on the population.

The fronto-parietal regions have been associated with many executive functions such as distractor inhibition, task switching and fluid intelligence (39). The overlap between the n-back regions and the dorsal attention network (DAN) and fluid intelligence were observed in this study, specifically in post-AWN exposure for all loads.

In the current study, the neural activation of MFG, insula and ACC were found in the WM task after the exposure to GWN, and less pronounced in the AWN condition. It can be suggested that the provision to GWN was efficient at modulating both effortful attention and working memory components as opposed to AWN. The activation of the ACC in 0-back condition indicates that the exposure to GWN was pivotal in improving effortful attention, consequently, better response accuracy.

The RT after the AWN along with GWN condition worsened, this has been found earlier (7). The activation of the left precentral gyrus is proposed to facilitate fast responses in a verbal WM task (45) was not observed in post-AWN condition, indicating that its exposure may have inhibited the fast response. The activation of precentral gyrus, however, was found in lower load post-GWN. Exposure to these BB may likely have slowed down the processing speed of participants, however, possibly enabled better response accuracy of the participants.

Larger activation in the left SFG during 3-back>1-back, 3-back>0-back contrast post-AWN were observed and is commonly found in n-back task paradigm. The activations of this region is associated with the updating and task switching role on a WM task (46). However, this contradicts the behavioural outcome, which shows the longest reaction time and the lower response accuracy. The lack of parietal region recruitment in higher load contrast 3-back> 0-back and 3-back>1-back may have been attributed to the distractor inhibition mechanism (36). A suggestion would be that the role of AWN in medium load is to capture, maintain and update the gained information. However, it is prone to distractibility.

Compared to the baseline condition, lesser activation of associated brain regions (see Table 1) in post-BB exposure were found, it can be assumed that the proponent is the neural efficiency hypothesis. It has been suggested that the decrease activation in associated WM regions is due to the neural circuits that are involved in the n-back task has improved in their efficacy, and the regions which are irrelevant to task performance have been inhibited (41).

As observed in the behavioural measures, RT during 3-back is longer in the post-AWN and GWN, suggesting that the exposure to BB may have contributed to slower processing speed. However, it has been suggested that slower processing speed amongst young adults may indicate a better cognitive control and observed better response accuracy were recorded post-AWN and GWN (47). The involvement of left SMG in lower loads in both post-BB condition points at an interesting angle, based on Guidali et al. (48), the region is associated with sequence processing and temporal order information. It is likely that the response accuracy in the post-BB condition could be explained through less error is made upon BB exposure. The better response accuracy in post-GWN may be due to the involvement of both SMG and SMC, notably, the SMC is absent in post-AWN contrasts. Working together, both SMG and SMC are responsible for encoding and maintaining the order of the stimuli (49).

The activation of right PCG was observed in post-GWN during 3-back in comparison to post-AWN. These regions are involved in updating, recalling sequential information and task switching mechanisms required in WM performance. Therefore, the better updating in the GWN condition may have contributed to the better response accuracy as participants were more adept at renewing the maintained information.

Both post-BB conditions exhibits the activation of the precuneus in lower load contrast 1-back>0-back, the region may have been responsible for controlling attentional shifts (50) as the n-back task load were given at random, aids participants when shifting from one load to another. The activation of the angular gyrus were also found post-BB that is associated with response inhibition during information retrieval (11), its involvement aided in improving the response accuracy of participants.

## CONCLUSION

As to our knowledge, the current study is the first in embedding the provision of pure tone binaural beats with white noise using fMRI as a modality. Further, we have utilised pink noise provision in an attempt to reduce possible carryover entrainment. The preliminary findings of this study lead us to conclude that exposure to AWN and GWN improves the response accuracy of the participants. Even so, the worsening reaction time suggests a longer processing speed that have taken place. In addition, the recruitment of the regions modulated by both AWN and GWN differ; AWN centers the well-established WM regions while GWN focuses on enhancing the regions involved in effortful attention. The study is limited in its sample size and a larger sample size is necessary to provide inferential statistics, which would allow better generalisation of the findings to a population. The suggestion to impose a combination of embedded BB or utilising multiple BBs may be beneficial in the future as the brain oscillation relies on multiple frequency ranges in memory processes.

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