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Artikel Asli / Original Article

Effects of Background White Noise on Auditory Working Memory Area Activation: Preliminary Outcomes among Adolescents with and without Internet Gaming Addiction

Kesan Latar Belakang Hingar Putih ke atas Pengaktifan Kawasan Ingatan Kerja Auditori: Dapatan Awal dalam kalangan Remaja dengan dan tanpa Ketagihan Permainan Internet

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ABSTRACT

Internet gaming addiction (IGA) has been associated with changes in neural function, particularly in auditory working memory (AWM) processing, especially in the presence of noise. White noise (WN) has been shown to enhance AWM performance through stochastic resonance (SR). However, the optimal noise level for performance enhancement remains unclear. The aim of this study was to determine changes in neural activation among adolescents without addiction (NIGA) and with addiction (IGA) symptoms during AWM task performance in the presence of different WN levels. It is hypothesised that WN at a certain sub-optimal level will increase brain activation via moderate brain arousal (MBA). 16 participants (8 NIGA, 8 IGA) performed an AWM task in four different WN backgrounds (intensity level = 45, 50, 55, and 60 dB) during a functional magnetic resonance imaging (fMRI) session. Brain structural and functional images were acquired via a 3-T Siemens Skyra system and analysed using a statistical parametric mapping framework (SPM25). Whole-brain random-effects analyses (RFX) revealed no significant differences ($pFWE < 0.05$) among the participants due to addiction at all noise levels. However, region-of-interest (ROI) analyses showed distinct noise-dependent activation patterns in the primary auditory cortex, with peaks at 50 dB and 55 dB for the NIGA and IGA groups, respectively. WN at a moderate intensity level aroused AWM-related brain areas consistent with SR phenomena. The different optimal intensity levels between groups suggest that individualized WN levels may have potential as a non-invasive approach to support cognitive processing in adolescents.

Keywords: Addiction, adolescent, gaming, memory, noise, resonance, stochastic

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ABSTRAK

Ketagihan permainan internet (IGA) dikaitkan dengan perubahan fungsi neuron khususnya dalam pemprosesan ingatan kerja auditori (AWM) terutama dengan kehadiran hingar. Hingar putih (WN) dilaporkan meningkatkan prestasi AWM melalui mekanisme resonans stokastik (SR). Namun, aras hingar optimum untuk peningkatan prestasi AWM masih belum difahami. Matlamat kajian ini ialah untuk menentukan perubahan dalam pengaktifan neuron dalam kalangan remaja tanpa ketagihan (NIGA) dan dengan ketagihan (IGA) semasa perlaksanaan tugasan AWM dengan kehadiran WN yang berbeza arasnya. Dihipotesiskan bahawa WN pada satu aras sub-optimum akan meningkatkan pengaktifan otak melalui kebangkitan otak sederhana (MBA). 16 subjek (8 NIGA, 8 IGA) melaksanakan tugasan AWM dalam empat latar belakang WN berbeza (aras keamatan = 45, 50, 55 dan 60 dB) semasa sesi pengimejan resonans magnet kefungsian (fMRI). Imej struktur dan kefungsian diperoleh melalui system MRI Siemens Magnetom Skyra 3T dan dianalisis menggunakan pemetaan statistik berparameter (SPM25). Analisis kesan rawak (RFX) keseluruhan otak mendedahkan tiada perbezaan bererti ($pFWE < 0.05$) dalam kalangan subjek akibat ketagihan pada semua aras hingar. Walau bagaimanapun, analisis kawasan keutamaan (ROI) menunjukkan corak pengaktifan akibat hingar yang jelas dalam korteks auditori perdana dengan puncak pada 50 dB dan 55 dB masing-masing untuk kumpulan NIGA dan IGA. WN pada aras keamatan sederhana membangkitkan kawasan otak berkaitan AWM konsisten dengan fenomena SR. Perbezaan aras keamatan optimum antara kedua-dua kumpulan menunjukkan bahawa penyesuaian aras WN mengikut kumpulan berpotensi menjadi pendekatan bukan invasif untuk menyokong pemprosesan kognitif dalam kalangan remaja.

Kata kunci: Hingar, ingatan, ketagihan, permainan, remaja, resonans, stokastik

INTRODUCTION

The rapid growth of internet access in Malaysia has significantly influenced adolescents' digital behaviour. In 2024, internet penetration has reached 97.4% of the national population, reflecting continued expansion of digital connectivity and online engagement (Kemp, 2024). While this advancement has facilitated access to education, communication and entertainment, it has also contributed to a rise in problematic online behaviours, particularly internet gaming addiction (IGA). Recent national studies indicate that IGA is becoming increasingly prevalent among Malaysian youth. 3.5% of secondary school students across seven states met the clinical criteria for IGA (Mohamed et al. 2023), while 35% of adolescents in Northern Malaysia displayed signs of problematic gaming (Wan Yaacob et al. 2021), highlighting the urgency of addressing this behavioural trend.

The Diagnostic and Statistical Manual of Mental Disorders, 5th Edition, Text Revision (DSM-5-TR) recognises IGA as a condition requiring further study, outlining nine diagnostic criteria, including preoccupation, withdrawal, tolerance, loss of control and continued gaming despite negative consequences (American Psychiatric Association 2022). Previous research has shown that adolescents with IGA often exhibit structural and functional brain changes in response to gaming cues, particularly reduced performance in regions responsible for executive control, reward processing and working memory (Chang & Lee 2024; Chun et al. 2020).

Among the cognitive domains affected by IGA, working memory, especially auditory working memory (AWM), is of particular concern. AWM supports the temporary storage and manipulation of sound-based information, making it essential for academic learning and everyday functioning. In adolescents with IGA, reduced brain activation within memory-related networks has been linked to poorer working memory performance and difficulty sustaining attention during auditory tasks (Chang & Lee 2024; Lopez et al. 2024). This vulnerability is amplified during adolescence, a period marked by ongoing prefrontal maturation and strengthening of frontotemporal pathways critical for working memory (Arain et al. 2013).

Parallel to the rise of IGA, environmental noise exposure has emerged as an additional challenge for adolescents' cognitive performance in Malaysia. Research in Bandar Baru Bangi (Wen et al. 2023) and Batu Pahat (Tong et al. 2023) found noise pollution in the school environment surpassed World Health Organization guidelines (>60 dB), posing risks to speech comprehension, memory performance, and overall learning. Excessive background noise increases listening effort and cognitive load, thereby weakening AWM and hindering information processing in students (Sullivan et al. 2015).

Interestingly, not all noise is detrimental. Under controlled conditions, certain types of noise, particularly white noise (WN), may enhance cognitive performance through a mechanism known as stochastic resonance (SR). SR describes how moderate levels of external noise can improve neural signal detection in systems with suboptimal arousal or reduced neural efficiency (Mcdonnell & Abbott 2009). Evidence suggests that WN can improve attention and working memory in individuals with reduced baseline arousal or attention difficulties (Othman et al. 2020). Consistent with this

framework, WN has been shown to improve attention and working memory performance, with studies demonstrating enhanced word recall and altered brain activation patterns at signal-to-noise ratios between 10 and 5 dB, while performance deteriorates at 0 dB, reflecting an inverted-U relationship (Awada et al. 2022; Othman et al. 2019; Söderlund et al. 2024).

These findings carry important implications for adolescents with IGA. Given that IGA is associated with reduced prefrontal activation, altered arousal regulation and impaired executive function (Dong et al. 2021), individuals with IGA may differ in their responsiveness to WN. As the SR effect depends on the interaction between external noise and internal neural states, adolescents with IGA may experience either enhanced or diminished cognitive benefits depending on their baseline neural activation. Investigating this interaction may therefore clarify whether WN can serve as a compensatory mechanism to support AWM in populations with addiction-related cognitive vulnerabilities.

Despite promising evidence, several research gaps remain. First, limited studies have examined WN effects specifically on AWM-related brain activation in adolescents, particularly those with IGA. Second, the neural mechanisms distinguishing how IGA and non-IGA (NIGA) adolescents respond to varying WN intensities remain poorly understood. Finally, existing studies have not established whether the optimal WN level for enhancing AWM is consistent across groups or influenced by addiction severity. Addressing these gaps is essential for determining whether WN can be used as a non-invasive, low-cost cognitive enhancement tool for adolescents affected by IGA.

Therefore, this study aims to examine the effects of varying background WN intensities on AWM-related brain activation in adolescents with IGA symptoms compared with those without. By using functional magnetic resonance imaging (fMRI) to assess activation within key regions, including Heschl's gyrus and superior temporal gyrus (STG), this research will explore whether WN differentially modulates neural activity associated with auditory memory. In line with SR theory, it also seeks to identify the optimal noise intensity that maximises AWM performance for both groups. Findings from this research may have significant implications for educational interventions, clinical management of IGA and the development of non-pharmacological strategies to support cognitive functioning in adolescents.

MATERIALS AND METHODS

PARTICIPANTS

The required sample size was estimated using PS: Power and Sample Size Calculation software (version 3.1.2) based on a significance level of 0.05, statistical power of 80%, and a large effect size (Cohen's d = 0.8), which indicated an ideal sample size of approximately 27 participants per group. However, convenience sampling was employed due to the practical challenges of recruiting adolescents with symptoms of IGA who also fulfilled the eligibility criteria for MRI examination. Recruitment was conducted within the Klang Valley region. A total of 21 participants were successfully enrolled during the study period. Eligible participants were male or female adolescents aged 15 to 19 years, native Malay speakers, right-handed, and with normal hearing sensitivity for both ears as assessed using a pure-tone audiometry test. Individuals were excluded if they had a history of neurological or cognitive disorders, were taking psychoactive medications or stimulants, presented with MRI contraindications such as metallic implants or pacemakers, were claustrophobic, had AWM scores above 115, or were pregnant. The decision to include only right-handed participants was based on evidence by Tomasi and Volkow (2024), who reported significant handedness-related differences in functional connectivity, thus reducing inter-subject variability. All participants provided written informed consent before enrolment, and assent with parental or guardian consent was obtained for minors. Ethical approval was granted by the Universiti Kebangsaan Malaysia Research Ethics Committee (JEP-2024-563).

INTERNET GAMING ADDICTON LEVEL ASSESSMENT

Internet gaming addiction was assessed using a multi-instrumental approach grounded in both DSM-5-TR and International Classification of Diseases 11th Revision (ICD-11) diagnostic frameworks. DSM-5-TR defines IGA as a pattern of persistent and recurrent gaming behaviour leading to significant impairment or distress, as indicated by the presence of at least five out of nine clinical criteria within a 12-month period (American Psychiatric Association 2022). To operationalise these criteria, participants completed the Malay Version of the Internet Gaming Disorder Scale Short Form (IGDS9-SF), a validated instrument for Malaysian adolescents that assesses IGA symptoms across nine items rated on a five-point Likert scale (Ling et al. 2021). Endorsement of five or more items as "Often" or "Very Often" was used to classify participants as belonging to the IGA group. To enhance diagnostic precision, the Gaming Disorder Scale for Adolescents (GADIS-A) developed based on ICD-11 criteria, was also administered to assess cognitive-behavioural symptoms, negative consequences, and frequency of gaming-related impairment (Paschke et al. 2020). Diagnosis was confirmed when participants scored

≥9 on the cognitive-behavioural symptoms (CBS) and ≥5 on the negative consequences (NS) scales and reported gaming problems occurring "during longer periods" or "almost daily" on the final item. Individuals fulfilling DSM-5-TR and ICD-11 criteria were categorised as gaming-addicted, while those with low scores and no history of problematic gaming were included as controls. This combined approach ensured robust identification of IGA and strengthened the validity of subsequent neuroimaging and cognitive analyses.

AUDITORY STIMULI

The auditory stimuli were generated and processed using Audacity® recording and editing software (Version 2.1.3). The stimuli consisted of 30 sets of words, with each set containing four unrelated, familiar Malay words. To ensure linguistic consistency throughout the experiment, all selected words were two-syllable nouns. To standardise the recording conditions, the words were pronounced by a native female Malay speaker and digitally recorded within a sound-treated room to minimise environmental noise. The recorded audio files subsequently underwent editing to eliminate background static and artefacts. Finally, the intensity level of the targeted speech signals was standardised to 60 dB sound pressure level (SPL) to ensure consistent audibility across all trials. However, spectral equalisation was not specifically performed across the words or stimulus sets, although the stimuli were standardised for linguistic characteristics, recording conditions, and presentation intensity. During the fMRI scan, stimuli were delivered binaurally through MRI-compatible headphones at 60 dB. Background auditory conditions were manipulated by randomly introducing WN at four intensities: 45 dB, 50 dB, 55 dB, and 60 dB. The same sets of auditory stimuli were used across all four WN conditions, with the order of stimulus presentation randomized to minimize order and habituation effects. Only auditory materials were employed, as the objective of the study is to examine how externally added random noise modifies performance in an AWM context.

EXPERIMENTAL TASK AND PROCEDURES

Participants performed an auditory working memory task known as the backward word recall task (BWRT). In each trial, they listened to four Malay nouns presented sequentially, with each word lasting 0.7 seconds and separated by a 0.4-second inter-stimulus interval. The four-word sequence was therefore presented within 4 seconds, followed by an additional 4 seconds during which participants verbally recalled the words in reverse order. To prevent memory or repetition effects, no word sequence was repeated within the same condition. Verbal responses were scored based on correct reversed-order recall of each word. The BWRT was delivered together with one of four background white-noise intensities (45, 50, 55, or 60 dB), with the conditions randomised to reduce learning, anticipation, and fatigue effects. This procedure follows the paradigm established by Othman et al. (2020), ensuring standardised auditory timing and task administration across all participants. The task was performed inside a 3.0-Tesla MRI scanner (MAGNETOM Skyra, Siemens Healthineers, Erlangen, Germany) equipped with functional imaging capabilities, and participants wore MRI-compatible headphones for binaural auditory delivery and noise attenuation. The MRI scans were conducted at Tunku Ampuan Besar Tuanku Aishah Rohani (TABTAR) Hospital, Universiti Kebangsaan Malaysia (UKM).

fMRI PARADIGM

To minimise the interference of scanner-generated acoustic noise during auditory task presentation, sparse temporal sampling (STS) was used (Absatova 2016). Conventional MRI scanning produces loud gradient sounds that can mask auditory stimuli and reduce task performance. STS introduces short silent intervals in which the scanner remains inactive. All auditory working memory stimuli are delivered within these silent gaps, allowing participants to perceive the words clearly without contamination from scanner noise and thereby improving the accuracy of detecting neural responses associated with auditory processing. The paradigm follows the protocol established by Othman et al. (2020), consisting of alternating baseline (rest) trials and BWRT trials. Each trial lasts 12 seconds, corresponding to the inter-scan interval. During BWRT trials, participants hear four Malay nouns presented sequentially (0.7 s per word with a 0.4 s inter-stimulus interval) and are then given 8 seconds to verbally recall the sequence in reverse order. Word lists are randomised to avoid predictability. Four experimental conditions are administered, each pairing the BWRT with a different background white-noise intensity (45, 50, 55, or 60 dB). Each condition includes 30 BWRT trials, and all baseline–task sequences are randomised to reduce order effects and maintain engagement. The full fMRI session lasts approximately 30 minutes, during which the scanner alternates between rest periods and auditory working memory task periods while acquiring brain activation data. Fig. 1 shows the experimental task paradigm.

ACQUISITION, TEMPORAL AND SPATIAL PROCESSING

High-resolution structural images of the whole brain were acquired using a T1-weighted sequence (TR =

1900 ms; TE = 2.35 ms; flip angle = 9°; voxel size = 1 mm³; matrix = 256 × 256). Functional images were obtained using a T2*-weighted echo-planar imaging (EPI) sequence (TR = 10,000 ms; TE = 30 ms; TA = 2000 ms; flip angle = 90°; voxel size = 3 × 3 × 5 mm; matrix = 64 × 64). An 8-second silent gap was incorporated using STS to facilitate clear auditory stimulus delivery. Twenty-three axial slices were acquired in descending order, and a total of 240 volumes were collected across all experimental conditions.

Functional MRI data were pre-processed using Statistical Parametric Mapping (SPM25) software running on MATLAB 9.14-R2023b (MathWorks, Natick, MA, USA). The first four functional volumes were discarded to avoid magnetic saturation effects (Yusoff et al. 2013). Remaining images underwent slice-timing correction and realignment using a six-parameter rigid-body transformation to correct for head motion. Motion thresholds were set at 2 mm for translation and 2° for rotation, and all participants remained within these limits (Sladky et al. 2011). No participants' head movements exceeded the threshold. The functional images were then normalised to the Montreal Neurological Institute (MNI) template using affine registration and spatially smoothed with an 8-mm full-width at half-maximum Gaussian kernel to enhance signal-to-noise characteristics. Finally, a visual inspection of the normalised functional images was conducted for all participants to verify accurate alignment with the MNI template prior to statistical analysis.

DATA ANALYSIS

The whole-brain analysis was conducted using SPM12 implemented in MATLAB to identify significantly activated brain areas evoked during the auditory task and to explore activity patterns across conditions. To investigate differences across background WN conditions, analyses were performed to compare brain region activation 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 ($P < 0.05$; with family-wise error correction for multiple comparisons). Voxel-level thresholding was not applied to ensure all active voxels that survived the statistical threshold were included in the analyses. All clusters that survived this threshold were regarded as significantly activated cortical brain regions.

A region of interest (ROI) analysis was conducted using WFU PickAtlas (Maldjian et al. 2003) to assess the spatial extent of brain activation (in terms of the number of activated voxels) in specific brain areas. The ROIs were selected based on their roles in AWM processing, including the primary auditory cortex (PAC) and the prefrontal cortex (PFC) areas. The PAC regions include the bilaterally superior temporal gyrus (STG) and Heschl's gyrus (HG), which play a main role in auditory processing (Yusoff et al. 2016). We also included a subregion of the PFC, specifically the dorsolateral prefrontal cortex (DLPFC), given its well-established role in working memory processing (Emch et al. 2019).

The ROI analysis was conducted on individual functional data. A single-subject anatomical atlas was used to define image volume masks for each ROI. The mask was then applied to the individual statistical parametric map set at the statistical threshold of $P_{FWE} < 0.05$ to obtain activation statistics of that particular region. The total number of suprathreshold voxels (k) was extracted from the masked ROI. One-sample t-tests were performed to determine within-group activation for the NIGA and IGA groups, while two-sample t-tests were utilised to assess differential activation between groups. Statistical analyses were performed using JASP software version 0.95.4 (JASP Team, Amsterdam, The Netherlands). Due to the small sample size (N = 8 per group) and violations of the normality assumption, nonparametric analyses were applied. The Friedman test was utilised to determine activation differences across all WN intensities for all ROIs.

RESULTS

SELECTED PARTICIPANTS

Out of 21 participants who took part in this study, 8 participants had IGA. For a better comparison, this preliminary study analysed and compared fMRI data from 8 NIGA and 8 IGA participants, excluding the remaining five NIGA participants. The 8 NIGA participants were chosen randomly from the pool of NIGA participants.

DEMOGRAPHIC CHARACTERISTICS

The demographic characteristics of the participants are presented in Table 1. The NIGA group consisted of eight participants aged 15–19 years (18.25 ± 1.49 years), comprising four males and four females. The IGA group consisted of eight participants aged 17–19 years (18.50 ± 0.93 years), comprising seven males and one female.

GROUP WHOLE BRAIN ACTIVATION

A second-level random-effects analysis (RFX) of a one-sample t-test applied to each of the NIGA and IGA groups revealed significant whole-brain activations (p = 0.05 corrected for family-wise error) during the AWM task performed in the presence of four levels of background WN. A larger spatial extent of activation was observed for a lower

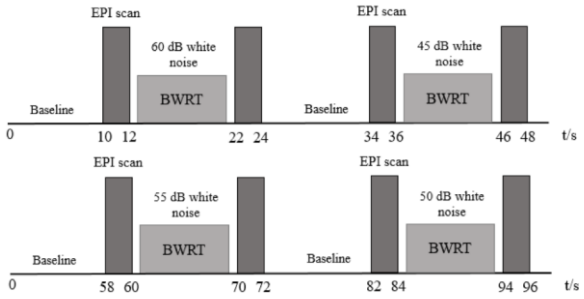


FIGURE 1 Schematic representation of the timing diagram for STS

TABLE 1: Demographic Characteristics of Participants in the IGA and NIGA Groups

Characteristics	IGA (*n*=8)	NIGA (*n*=8)
Age, mean ± SD (years)	18.50 ± 0.93	18.25 ± 1.49
Age range (years)	17–19	15–19
Male, n (%)	7 (87.5%)	4 (50.0%)
Female, n (%)	1 (12.5%)	4 (50.0%)

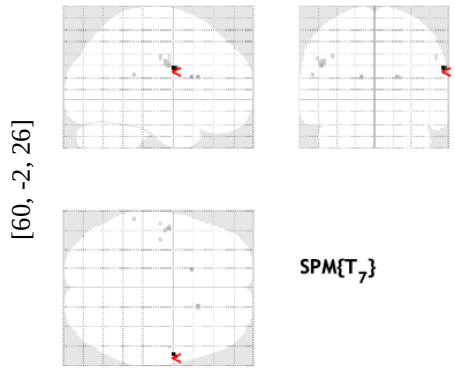
TABLE 2 Spatial extent of activation (*k*) in the Left and Right PAC and DLPFC for IGA and NIGA groups ($P_{FWE} < 0.05$)

Region	Noise Condition	IGA (Addicted) Mean ± SE	NIGA (Normal) Mean ± SE
Left PAC	45 dB	1074.75 ± 699.25	807.375 ± 483.06
	50 dB	1100.625 ± 568.53	875.625 ± 501.97
	55 dB	1114.25 ± 419.42	789.375 ± 486.28
	60 dB	1059 ± 503.16	783.5 ± 434.86
Right PAC	45 dB	1283.875 ± 878.97	1063.625 ± 690.46
	50 dB	1349.875 ± 617.97	1113.375 ± 680.12
	55 dB	1399.75 ± 487.77	940 ± 743.61
	60 dB	1300.125 ± 618.17	1123.875 ± 757.91
DLPFC	45 dB	175.625 ± 178.66	313.5 ± 353
	50 dB	254.625 ± 229.24	289.625 ± 312.05
	55 dB	221.5 ± 298.58	167.75 ± 152.18
	60 dB	194.75 ± 124.88	200 ± 210.28

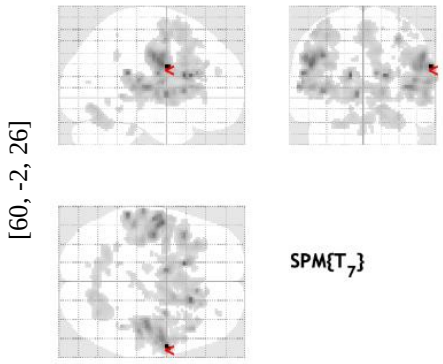
TABLE 3 Friedman Test results for activation differences across WN intensity levels

Region of Interest (ROI)	Group	Chi-Square (χ^2)	df	p-value	Significance
Left PAC	NIGA	0.450	3	0.930	Not Sig.
	IGA	0.000	3	1.000	Not Sig.
Right PAC	NIGA	1.950	3	0.583	Not Sig.
	IGA	0.045	3	0.930	Not Sig.
DLPFC	NIGA	1.500	3	0.682	Not Sig.
	IGA	0.600	3	0.896	Not Sig.

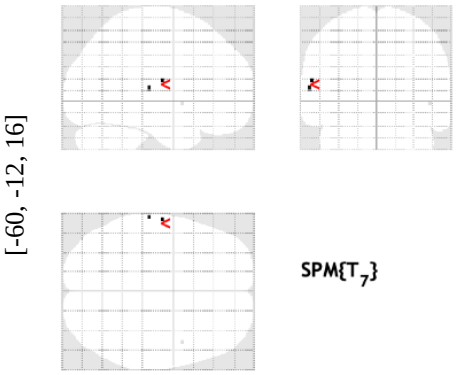
a) 45 dB ($p_{FWE} < 0.05$)



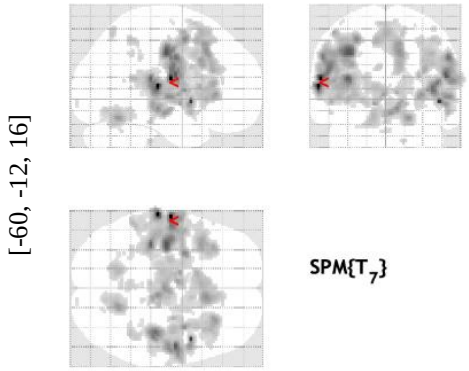
b) 45 dB ($p < 0.001$)



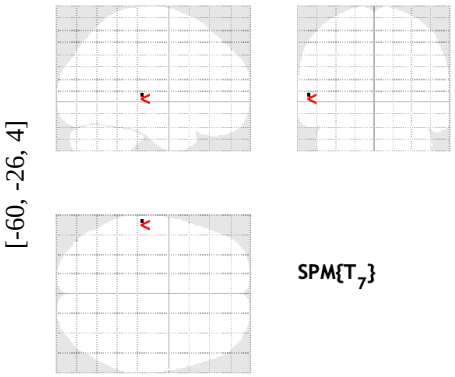
c) 50 dB ($p_{FWE} < 0.05$)



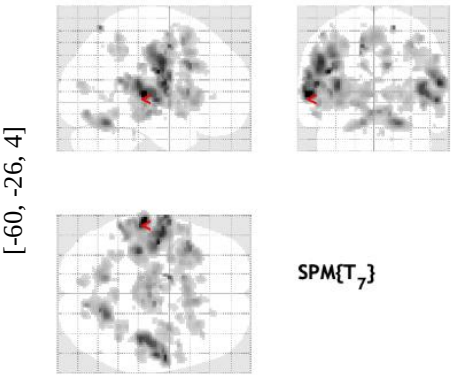
d) 50 dB ($p < 0.001$)



e) 55 dB ($p_{FWE} < 0.05$)



f) 55 dB ($p < 0.001$)



g) 60 dB ($p_{FWE} < 0.05$)

h) 60 dB ($p < 0.001$)

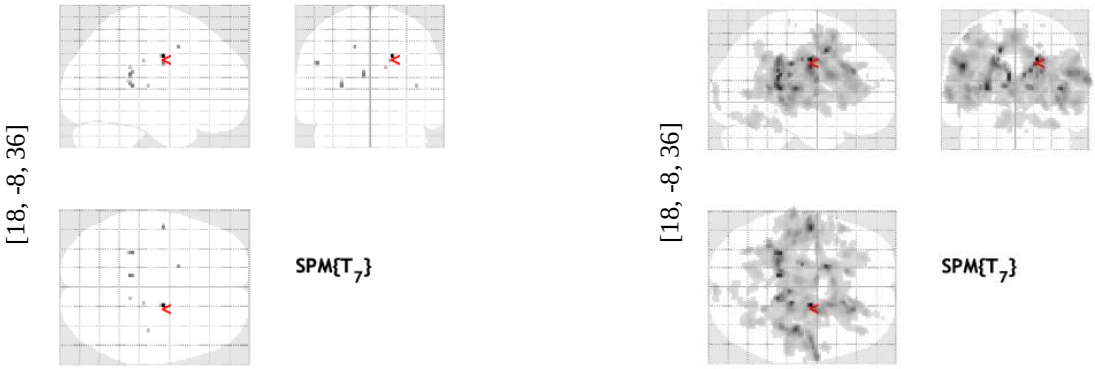
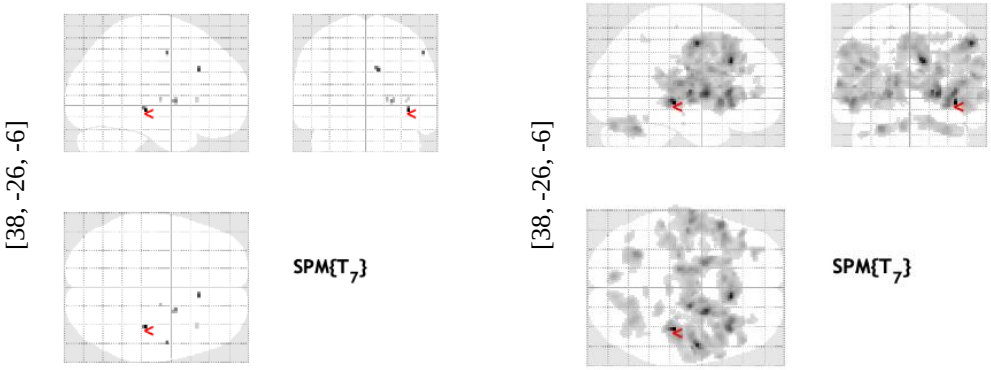


FIGURE 2 Maximum intensity projection of NIGA brain activation obtained from an AWM task in the presence of background WN. The red arrow in each image indicates the location of the global maximum activation peak for that specific condition. Due to the limited spatial extent of activation at the corrected threshold $p_{FWE} < 0.05$, maps are additionally presented at $p_{FWE} < 0.001$ uncorrected for clearer visualisation of activation patterns.

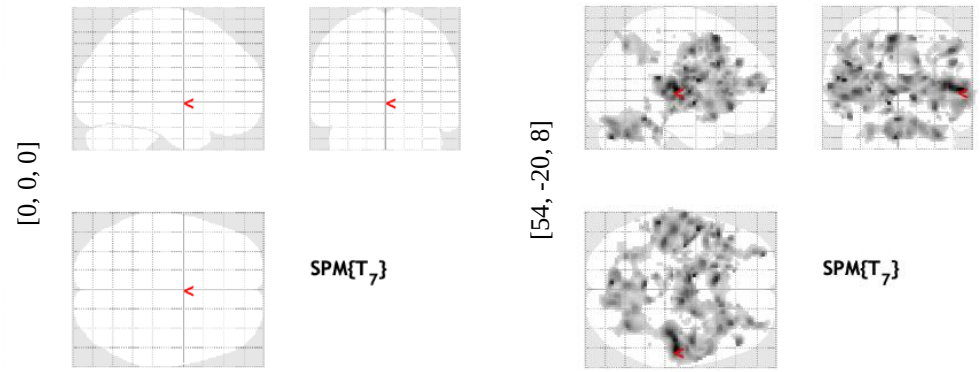
a) 45 dB ($p_{FWE} < 0.05$)

b) 45 dB ($p < 0.001$)

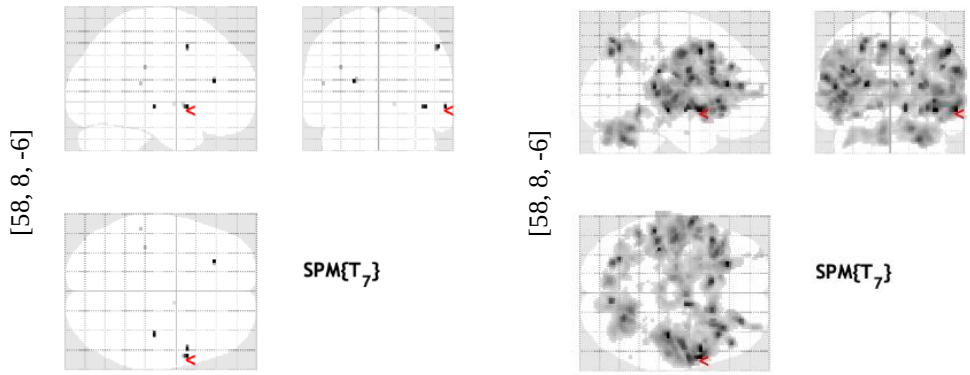


c) 50 dB ($p_{FWE} < 0.05$)

d) 50 dB ($p < 0.001$)



e) 55 dB ($p_{FWE} < 0.05$) f) 55 dB ($p < 0.001$)



g) 60 dB ($p_{FWE} < 0.05$) h) 60 dB ($p < 0.001$)

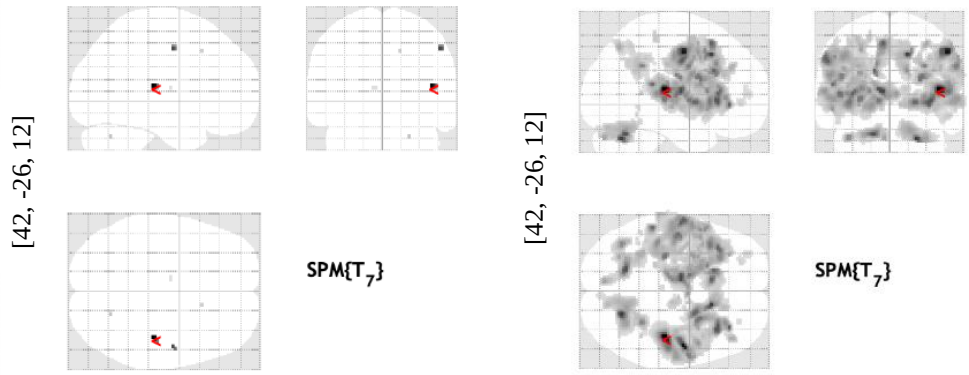
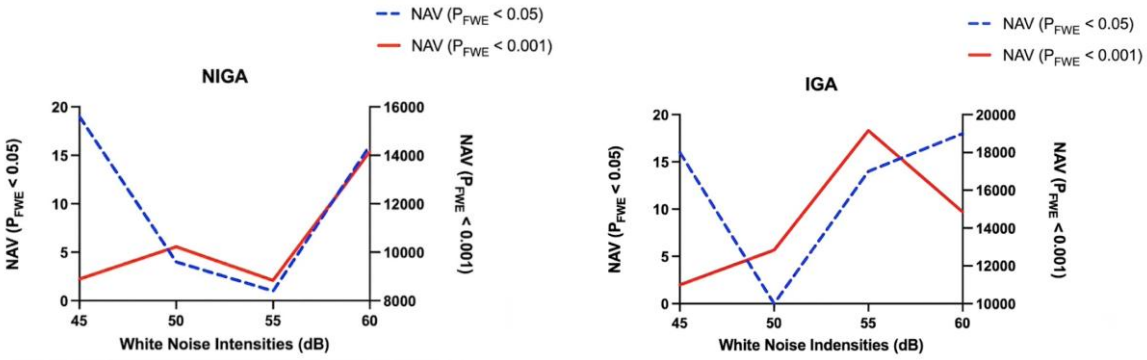


FIGURE 3 Maximum intensity projection of IGA brain activation obtained from an AWM task in the presence of background WN. The red arrow in each image indicates the location of the global maximum activation peak for that specific condition. Due to the limited spatial extent of activation at the corrected threshold $p_{FWE} < 0.05$, maps are additionally presented at $p_{FWE} < 0.001$ uncorrected for clearer visualisation of activation patterns.



(a) NIGA group (b) IGA group

FIGURE 4 Plots of NAV obtained from whole brain activation at corrected and uncorrected significant levels for (a) NIGA and (b) IGA groups for all intensity levels.

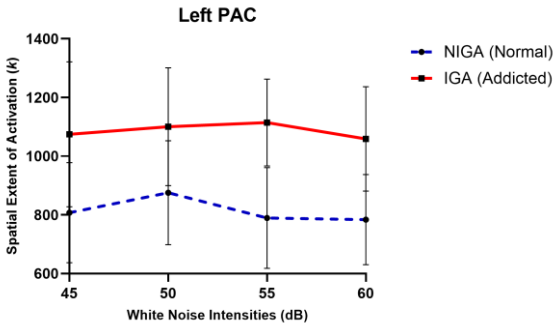


FIGURE 5 Plots of spatial extent of activation (*k*) at corrected significance level for the Left PAC mask for NIGA and IGA groups across all intensity levels. Error bars represent the standard error (SE).

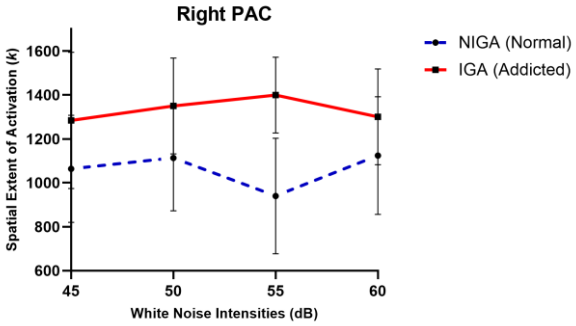


FIGURE 6 Plots of spatial extent of activation (*k*) at corrected significance level for the Right PAC mask for NIGA and IGA groups across all intensity levels. Error bars represent the standard error (SE).

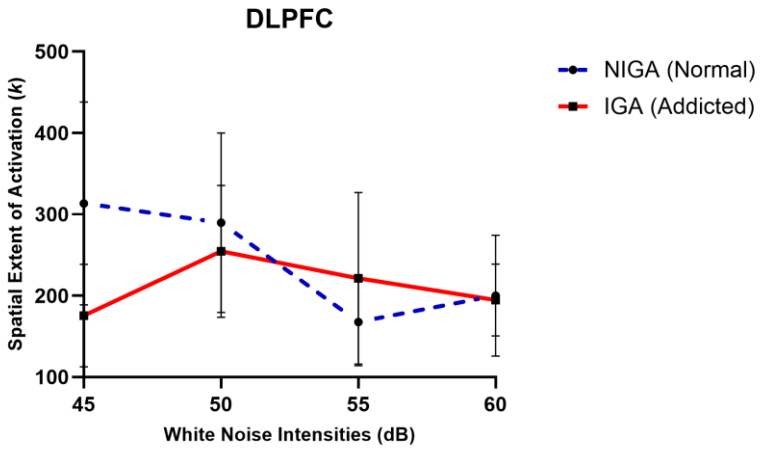


FIGURE 7 Plots of spatial extent of activation (*k*) at corrected significance levels for the DLPFC mask for NIGA and IGA groups across all intensity levels. Error bars represent the standard error (SE).

threshold (p = 0.001, uncorrected for family-wise error). Figs. 2 (a – h) show the activation profile obtained from the analysis performed on the NIGA group, while for the IGA group, the results are shown in Figs. 3 (a – h). A larger spatial extent of activation can be observed for a lower threshold for all intensity levels, but for each threshold, the spatial extent of activation represented by the number of activated voxels (NAV) changes dramatically for different intensity levels of WN, as can be seen in Figs. 4(a). The profiles reveal a marked inconsistency between the two statistical thresholds. We observed that uncorrected data display dynamic fluctuations characterised by distinct peaks and dips across noise intensities, but these patterns do not survive at the more stringent corrected threshold as shown in Figs. 4(b). Although the occurrence of SR was not statistically confirmed, the figure suggests a potential SR-like pattern at an intensity level of 55 dB on a p = 0.001 uncorrected threshold. In order to precisely determine the occurrence of SR, which is our primary objective, it is necessary to perform an ROI analysis for specific regions in the brain that are involved in the processing of AWM stimuli.

REGION OF INTEREST (ROI) ANALYSIS

To test our specific hypotheses regarding the occurrence of SR, we restricted subsequent analyses to ROI approaches, which offer greater sensitivity for detecting localised effects. The analyses were carried out on the bilateral PAC and PFC area, which is DLPFC. Both NIGA and IGA individuals revealed significant whole-brain activation (p = 0.05 corrected for family-wise error) during the AWM task performed in the presence of four levels of background WN. The analyses were conducted to measure NAV in three ROIs for each participant.

The mean NAV ± standard error (SE), representing the spatial extent of activation (*k*), is tabulated (Table 2) and illustrated graphically in Figs. 5 - 7.

To statistically validate the observed lateralization, a Wilcoxon signed-rank test was conducted. Results revealed a significant difference in overall activation between hemispheres (Z = 2.947, p = 0.002). Inspection of the median values confirmed a right-hemispheric dominance, with the Right PAC (Median = 1197) demonstrating significantly greater activation than the Left PAC (Median = 951) across all noise intensities for both groups. Furthermore, the average NAV for both PAC at all intensity levels is always higher in the IGA group than in the NIGA group.

From Figs. 5 and 6, even though the sign of occurrence of SR is not clear, the figures suggest that it should appear at an intensity level of 50 dB for the NIGA and 55 dB for the IGA groups. In the Left PAC, the NIGA group demonstrates a lower and more stable threshold, but there is a sign of peak activation at the moderate noise level pattern, characterised by a rise in NAV that peaks at 50 dB before declining. Similarly, the IGA group (solid red line) also demonstrates a peak activation at the moderate noise level of 55 dB. While in the Right PAC, the IGA group maintained a similar trajectory, with activation again peaking at 55 dB. In contrast, the NIGA group did not exhibit a peak at this intensity but instead showed fluctuations in NAV.

For DLPFC shown in Fig. 7, the NIGA group (blue dashed line) shows a descending trend, with minimal NAV observed at 55 dB, followed by an increment as noise intensity increased. In contrast, the IGA group (solid red line) demonstrated a clear peak at 50 dB. However, unlike PAC, the NAV for the IGA group is also not always higher than that of the NIGA group.

A non-parametric Friedman test was conducted to evaluate differences in neural recruitment across four noise-intensity levels (45, 50, 55, and 60 dB). As summarised in Table 3, the analysis did not show statistically significant differences in activation volumes for the Left PAC, Right PAC, or DLPFC in either the IGA or NIGA groups ($p_{FWE} < 0.05$). For instance, the Left PAC in the IGA group showed a Chi-Square value of 0.00 ($p > 0.05$), indicating that individual rank variations effectively cancelled out across the cohort. This lack of statistical significance is likely attributable to high inter-subject variability in spatial localisation and neural strategy, a common challenge in neuroimaging studies with modest sample sizes.

DIFFERENTIAL ANALYSIS

To examine between-group differences, differential contrasts (IGA > NIGA and NIGA > IGA) were computed for each background noise condition for all ROIs. However, these analyses showed no statistically significant differences in activation maps between the two groups at the corrected threshold ($p_{FWE} < 0.05$).

DISCUSSION

This study investigated the effects of varying background WN intensities on AWM-related brain activation in adolescents with NIGA compared to adolescents with symptoms of IGA, within the framework of SR. Specifically, the study examined group differences in neural activation patterns and identified noise intensities that may optimally support AWM processing in each group.

The absence of large clusters of activation in the whole-brain analysis at a corrected significant level for both groups is likely attributable to high inter-subject variability in spatial activation patterns, rather than an absence of neural engagement. Previous addiction studies have shown that the addicted brain often exhibits scattered and less spatially consistent activation due to compensatory recruitment of broader neural networks (Dong et al. 2011). As a result, although individual activation volumes may be high, low spatial overlap across participants can lead to non-significant group-level maps.

Dynamic fluctuations characterised by distinct peaks and dips were observed across noise intensities in the corrected and uncorrected data for whole-brain activation. In contrast to previous studies that consistently reported distinct activation peaks (Mcdonnell & Abbott 2009), the present findings demonstrated a fluctuating pattern of peaks and dips. These inconsistencies may be attributed to the small sample size (*N* = for each group*)* compared with the estimated sample size, which limits the statistical power required for robust whole-brain analysis. In this context, ROI analysis provides a more sensitive, hypothesis-driven approach to examining activation within specific AWM-related regions.

ROI analysis of the bilateral PAC revealed distinct activation profiles between the NIGA and IGA groups. The NIGA group showed a relatively stable and lower-magnitude activation pattern across increasing WN intensities, without a pronounced inverted-U-shaped curve. This stability likely reflects efficient baseline auditory processing, reducing reliance on external noise to facilitate sensory encoding. Such findings are consistent with the moderate brain arousal (MBA) model, which suggests that individuals with optimal baseline neural efficiency derive limited benefit from added noise (Neubauer & Fink 2009).

In contrast, adolescents with IGA exhibited a more pronounced peak activation at moderate noise levels across noise intensities, with activation increasing from 45 dB, peaking between 50 dB and 55 dB, and declining at 60 dB. This pattern is more

closely aligned with SR theory, which proposes that moderate levels of external noise can enhance neural signal detection in systems operating under suboptimal baseline conditions (Mcdonnell & Abbott 2009). The presence of this SR-like response suggests that auditory sensory processing in adolescents with IGA may benefit from moderate background noise, which can enhance weak or inefficient neural signals.

Across both groups, greater activation was observed in the Right PAC compared to the Left PAC. This rightward asymmetry may reflect functional specialisation of the auditory cortex, as the right hemisphere is more involved in processing spectral characteristics and background sound textures, such as WN (Albouy et al. 2020). In addition, the increased engagement of the Right PAC may represent a compensatory mechanism. Although AWM for verbal material is typically left-lateralised, the introduction of background noise increases listening difficulty and cognitive load, prompting recruitment of contralateral auditory regions to support signal-to-noise (SNR) separation and sustained attention.

Across all noise conditions, the NIGA group consistently exhibited descriptively lower PAC activation volumes compared with the IGA group. For example, at 55 dB in the Right PAC, activation volume in the NIGA group was substantially lower than that observed in the IGA group (940 vs. 1400 voxels). This contrast supports the neural inefficiency hypothesis, whereby the addicted brain requires recruitment of larger neural resources to achieve comparable processing outcomes. In comparison, the healthy brain processes sensory input using more precise and metabolically efficient networks (Neubauer & Fink 2009). Similar compensatory hyperactivation patterns have been reported in neuroimaging meta-analyses of IGA, attributed to deficits in baseline neural tuning and inefficient executive regulation (Niu et al. 2022; Zhu et al. 2025).

Examination of the DLPFC further revealed group differences in top-down executive control. The observed crossover interaction in the DLPFC is consistent with the compensatory hyperactivation model of addiction. While the NIGA group demonstrated an efficient, linear recruitment of executive resources, the IGA group exhibited a dysfunctional non-linear profile. The blunted activation at 45 dB reflects a failure to initiate top-down control, a deficit confirmed by recent meta-analyses of the Executive Control Network in IGA (Niu et al. 2022). However, at 50 dB, the IGA group exhibited a surge in activation, suggesting a compensatory effort to maintain cognitive performance despite neural inefficiency. These dynamic parallel the findings of Zhu et al. (2025), who described prefrontal dysregulation in adolescents, where neural recruitment must be substantially increased to match the performance of healthy controls, until the cognitive demand ultimately exceeds processing capacity.

Taken together, these findings indicate a functional imbalance between bottom-up sensory processing and top-down executive control in adolescents with IGA. Compared to the NIGA group, adolescents with IGA show enhanced auditory cortical activation alongside delayed or inefficient DLPFC recruitment, suggesting greater reliance on sensory amplification rather than executive regulation during AWM tasks. This imbalance may contribute to difficulties in filtering irrelevant auditory information and sustaining attention in noisy environments commonly encountered in academic settings.

Regarding optimal noise intensity, the results indicate that moderate WN facilitates auditory cortical activation in both groups, though with distinct intensity thresholds. Specifically, the IGA group exhibited maximal activation at 55 dB, consistent with the SR profile. In contrast, the NIGA group showed an earlier peak at 50 dB, suggesting greater sensitivity to auditory modulation. This differential response, in which the optimal level shifts by 5 dB between groups, indicates that the benefits of WN are state-dependent. The neural inefficient (IGA) brain likely requires slightly higher external noise to achieve the same stochastic facilitation as the healthy brain. Importantly, both groups showed reduced activation at 60 dB, confirming that excessive noise negates potential cognitive benefits regardless of addiction status.

These findings have practical implications for educational and clinical contexts. Controlled WN may serve as a supportive intervention for adolescents with IGA during auditory-based tasks. However, noise levels should be carefully optimised and individualised. Uniform application of WN without consideration of individual neural state may be ineffective or counterproductive. Several limitations should be acknowledged. The small sample size (*N=16*) may limit statistical power and generalizability. In addition, although the auditory stimuli were standardized for linguistic characteristics, recording conditions, and presentation intensity, spectral equalisation was not performed across the words or stimulus sets. Therefore, variations in spectral characteristics may have contributed to differences in auditory cortical activation. Behavioural performance measures were also not directly correlated with neural activation in the present analysis. Future studies should incorporate larger samples, acoustically matched or spectrally equalised auditory stimuli, behavioural–neural correlations, and connectivity analyses to further elucidate the interaction between sensory and executive networks. Longitudinal and intervention-based designs may also clarify whether WN can be

used as a sustained cognitive support strategy for adolescents with IGA.

CONCLUSION

The findings indicate that background WN modulates AWM-related brain activation differently between adolescents with and without IGA symptoms. While whole-brain between-group analyses did not reveal statistically significant differences at the corrected threshold, ROI analyses demonstrated distinct noise-dependent activation patterns in auditory and executive regions. NIGA adolescents showed inconsistent auditory cortical activation across intensity levels, whereas adolescents with IGA symptoms exhibited a peak at moderate noise levels, approximately 55 dB for the bilateral PAC and 50 dB for the DLPFC. These patterns found in the IGA group are consistent with SR theory, suggesting that moderate WN may enhance auditory processing, particularly in individuals with reduced baseline neural efficiency. Overall, the results indicate that optimal noise intensity is group-dependent and that carefully calibrated WN may support auditory working memory performance in adolescents with IGA.

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