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The Impact of Auditory White Noise on Cognitive Performance

Nicole Baum
Jasleen Chaddha

Although noise has often been characterized as a distractor, contemporary studies have emphasized how some individuals' cognitive performance could benefit from task-irrelevant noise. Usually these studies focus on sub-attentive individuals and/or those who have been diagnosed with ADHD. An example of task-irrelevant noise is white noise (WN). Research regarding the effectiveness of WN in healthy adults has provided mixed results and therefore, the implications of WN remain unknown. The objective of this study was to determine the effects of WN on the cognitive performance of the neurotypical population. To test this, participants were asked to complete simultaneous amplitude discrimination and temporal order judgement (TOJ) tests several times in the presence of varying levels of WN. Participants were split into two groups––one containing individuals with regular prior WN exposure and the other with no previous experience with WN. The performances of participants with prior exposure to WN, but not those without prior exposure, resembled a U-shaped tuning curve for simultaneous amplitude discrimination. This indicates that familiarity with WN moderates its effectiveness on cognitive improvement. TOJ was not found to be affected by varying levels of WN intensity. The results of this study emphasized that there is a possibility that WN could facilitate higher levels of cognitive performance, though there is likely an adjustment period associated with its introduction to daily life. This warrants that additional research should be conducted in order to cultivate a definitive conclusion about the effects of WN.

Citation

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Introduction

Noise is often perceived to be detrimental to cognitive ability [1]. For much of the twentieth century, noise was deemed as a distractor that removed attention from the target task and easily disturbed cognitive processing [2]. However, a contradicting study published in 1996 asserted that participants could benefit from task-irrelevant noise presented along with the target task under certain conditions [3]. The present study explores this phenomenon more closely in healthy adults with no attentional or cognitive deficits. Specifically, the objective of this study is to determine the effects of differing volumes of white noise (WN) on cognitive performance. WN is task-irrelevant auditory input containing many frequencies of equal intensities [4]). This research is significant because it directly addresses a method that has potential to boost cognitive performance in neurotypical populations. This pilot study is among the first few research projects investigating this query. Though a lot of studies have focused on the effects of WN on sub-attentive individuals and those who have been diagnosed with attention deficit hyperactivity disorder (ADHD), only a small portion of research has been dedicated to studying these effects on a neurotypical population. Moreover, there appears to be many contradictions in how effective WN is in the research that has been published. Consequently, the implications of WN remain largely unknown.

WN is processed in the brain in the same manner as any other noise. Once noise is created, sound waves from the point of origin travel to the outer ear. The sound waves specifically enter the ear canal, which leads to the eardrum. The eardrum responds to contact with sound waves by vibrating and then transmits these vibrations to the bones of the middle ear––the malleus, incus, and stapes [5]. These bones increase or amplify the sound vibrations so that they could be sent to the cochlea, a fluid-filled structure in the inner ear. Sound vibrations cause the fluid inside the cochlea to ripple, sending waves across the basilar membrane––an elastic partition that separates the ‘upper’ and ‘lower’ regions of the cochlea [5]. Hair cells function as sensory cells on the basilar membrane and sense the wave travelling across the basilar membrane. Hair cells near the center of the cochlea detect lower-pitched sounds and those closer to the wide end of the cochlea detect higher-pitched sounds [5]. Microscopic hair-like projections that are on top of hair cells, called stereocilia, collide with the overall structure of the cochlea and bend [5]. Bending causes pore-like channels to open at the ends of the stereocilia, causing different chemicals to rush into the cells. This electrical signal is carried by the auditory nerve, which is a bundle of nerve fibers that carry information between the cochlea in the inner ear and the brain [6]. The vestibular nerve, which carries information regarding balance from the semicircular canals, and the auditory nerve come together to form the vestibulocochlear nerve––the eighth cranial nerve [5]. The vestibulocochlear nerve carries information to the temporal lobe of the brain, in which the sound is processed. This determines how the sound is perceived [6]. Hearing and processing sound can also affect cognition.

Stochastic resonance (SR) is the counterintuitive phenomenon in which an optimal amount of noise becomes beneficial for cognitive performance under certain circumstances [1]. A multitude of noisy inputs are received by the brain, and of these signals, only a few are of importance. The central nervous system must distinguish between noisy neuronal inputs and task-relevant components [7]. Essentially, this model stipulates that the detection of a subthreshold signal is enhanced by the addition of noise [1]. The addition of noise to the original subthreshold signal allows the overall signal to pass a certain threshold, facilitating detection [8]. It does this by increasing the signal-to-noise-ratio (SNR). The signal being the stimuli one is actually trying to attend to, and the noise being irrelevant input. When the SNR is raised, the threshold for detection can be surpassed [7]. SR is present in the biological sensory systems of both animals and humans [9]. Furthermore, this psychophysical phenomenon has been found to occur in several modalities including hearing, tactile, and vision [8]. Moreover, many studies have explored the SR effects when the signal and noise are from separate modalities and it has been found that SR can be observed cross modally [10]. For example, auditory noise has been found to be helpful in the detection of visual stimuli presented at subthreshold levels [10]. In addition to being helpful with perception, the effects of SR have also been found to be beneficial to central cognitive processes as seen in a study in which auditory noise was shown to improve the speed of arithmetic computations in a neurotypical population [11].

SR is usually quantified by plotting cognitive performance as a function of noise level, revealing an inverted U-shaped curve. This indicates that the best cognitive performance occurs at moderate levels of noise, whereas, too much or too little noise attenuates performance [1]. Although increased neural noise has been found to improve performance on many cognitive tasks, only certain types of noise have been found to be beneficial. In regard to auditory noise, the presented noise must be unrelated to the task at hand in order to promote SR effects [12]. Further, it must have high levels of energy at all frequencies and must be continuous, as to not negatively affect attentional allocation [1]. For these reasons, WN has been a popular choice amongst researchers for the induction of SR effects in participants.

SR is a fundamental mechanism that contributes to the moderate brain arousal model (MBA model), an overarching model that further outlines how WN may be beneficial to cognitive performance [4]. The MBA model postulates that noise in the environment introduces internal neural noise into the central nervous system via the perceptual system [7]. Therefore, certain thresholds of noise could stimulate an optimal level of cognitive performance [7]. The amount of noise required to reach an optimal level of performance is modulated by levels of dopamine in the nervous system [7]. For example, if an individual has naturally lower levels of dopamine, then the addition of noise would allow them to reach their optimal range of cognitive performance. Additionally, people who have reduced dopamine levels would require greater amounts of noise in order to elicit maximal cognitive performance than control individuals [7]. Individuals with lower levels of dopamine are often individuals that are sub-attentive, and may even suffer from ADHD [4].

Due to their deficits in dopamine signaling, WN has been found to be particularly advantageous in populations with ADHD. In a study conducted to compare the effects of stimulant medication to those of 80 dB WN on cognitive tasks (n-back task, word recall, and spanboard) performed by children with ADHD, the children who listened to WN during these tasks displayed significant improvements in their performance while those on stimulant medication did not display such improvements [13]. Additionally, WN has been found to be beneficial in populations suffering from cognitive deficits such as those diagnosed with Alzheimer’s disease [14]. In their study, Belleville et al. discovered that the working memory performance of patients with Alzheimer’s was improved if they listened to WN concurrently while completing a task [14].

Although the previous literature clearly shows cognitive performance improvement in those with attentional and cognitive challenges, there is much contradiction in the literature as to whether WN is beneficial to neurotypical populations during the completion of cognitive tasks. In a study performed on healthy adults investigating the effects of SR on the speed of retrieval for single digit multiplication rules, researchers found that participants performed optimally at 77 dB [11]. Further, they tested participants’ performance at six separate levels of auditory noise ranging from 51 to 90 dB and were able to map the U-shaped curve of performance that is displayed in SR phenomena [11]. A later study in healthy young adults found that participants displayed a U-shaped performance curve under four different intensities of WN on an auditory working memory task [15]. This finding corroborates the predictions of the SR and MBA models. Conversely, in another study testing the cognitive performance of school children categorized as either sub-, normal, or super-attentive under three different intensities of WN (65-85 dB), it was found that the sub-attentive children benefited from the addition of WN, while the normal children saw no effects, and the performances of the super-attentive children degraded as sound intensity increased [4]. Additional studies have displayed similar findings in populations without attentional deficits. However, Helps et al. offer a possible reason for these discrepancies. They posit that the inverted U-shaped function of performance may be shifted right for sub-attentive children when compared to normal or super-attentive children [4]. That is, perhaps sub-attentive children require greater intensities of noise to achieve SR effects while normal and super-attentive children require lower intensities of noise [4]. So, perhaps the issue is not that healthy populations do not experience the effects of SR. Rather, previous studies have primarily focused on comparing individuals with ADHD to normal populations, and have thus not examined lower ranges of WN in order to induce SR effects in healthy individuals.

The present investigation intends to determine whether or not WN can be beneficial to neurotypical populations. Specifically, the authors hypothesize that healthy adults with no prior clinical diagnoses of cognitive or attentional deficits will display the inverted U-shaped curve of performance postulated by the SR and MBA models. Further, the authors hypothesize that the optimal levels of WN for the participants will be much lower than that seen in previous studies in individuals with ADHD. As most previous studies focusing on ADHD have found an intensity of approximately 70-80 dB of WN, this study will focus on lower ranges. To investigate this topic, simultaneous amplitude discrimination and temporal order judgement (TOJ) tasks will be administered via the Brain Gauge apparatus. This device applies vibrotactile stimulation to the fingertips of its users. The authors selected these particular tests as WN has not been found to be helpful in all aspects of cognition [16]. The objective is to identify additional facets of cognition that the performance of which can be modulated by the introduction of WN into the neural system.

Methods

Participants

Seven volunteers participated in this study. Participant ages ranged from 18-54 years (mean age = 36.71 years, SD = ± 16.06 years). The majority of participants were cisgender females (71.4% female, 28.6% male). Participants were Caucasian (42.9%) and south Asian (57.1%). All participants reported no prior history of clinically diagnosed cognitive or attentional deficits. All participants were naive to the technology and tasks performed in this experiment. In regard to prior use of WN, 42.9% of participants reported having listened to WN either at work or while studying. No incentive was offered to participants in return for their participation. Each participant provided their informed consent and were instructed that they were free to withdraw from the study at any point in the duration without repercussions.

Materials

All tests of cognitive performance were delivered by the Brain Gauge device designed by Cortical Metrics (see corticalmetrics.com for additional information). The computer mouse-shaped device is designed to deliver vibrotactile stimulation to the index and middle finger of the participant’s dominant hand. The device is plugged directly into a personal computer via USB and the data from each test automatically uploaded onto the Brain Gauge app.

Test Battery

This study utilized two cognitive tests administered via the Brain Gauge device. In order to task multiple areas of cognition, participants were asked to complete simultaneous amplitude discrimination and temporal order judgement (TOJ) tests. The amplitude discrimination test requires participants to determine which of two vibrations delivered to the index and middle finger simultaneously are of greater intensity. The test involves five separate levels. Each level reached employs greater difficulty as the discrepancy between the two stimuli shrinks. The TOJ test involves sequencing and asks participants to determine which of two pulses, delivered to the index and middle finger, came first. This test is also composed of five levels and becomes increasingly difficult as the two stimuli are delivered with less and less latency. On both tests, participants indicate the correct answer by pressing down on the corresponding vibrotactile tip. Although each task employs executive functioning, each test demands different skills and engages differing aspects of cognitive processing.

Auditory Stimuli

For all WN experimental conditions, researchers played WN created by the artist Electric Dreams. The noise was administered via soundproof headphones from an iPhone. In this study, 5 different intensities of WN were employed. Each participant completed the test battery in presence of 0 dB, 12.8 dB, 25.5 dB, 38.3 dB, and 61 dB (0%, 12.5%, 25%, 37.5% and 50% of total iPhone volume, respectively) over a series of separate trials.

Procedure

Each participant was asked to complete the test battery at each of the five sound levels. Additionally, they were asked to complete the test battery at each sound level a total of three times. The order in which participants completed the test battery for the differing sound levels was randomized for each participant. During testing, participants were instructed to stay seated in front of a table so that the Brain Gauge apparatus could rest on a flat surface. Further, participants were instructed to keep their eyes open throughout testing and to focus on the computer screen. All tasks were completed using the participants’ dominant hands. Once testing began, participants were required to keep their hands on the device with their index and middle finger positioned over the vibrotactile tips. After participants completed the three repetitions of the test battery for a single sound level, they were asked to rate how distracting they found the auditory stimuli at that particular intensity on a 10-point scale (1 = not distracting at all, 10 = extremely distracting). After completion of the test battery at all sound levels, participants were debriefed on the purpose and goals of the study.

Figures

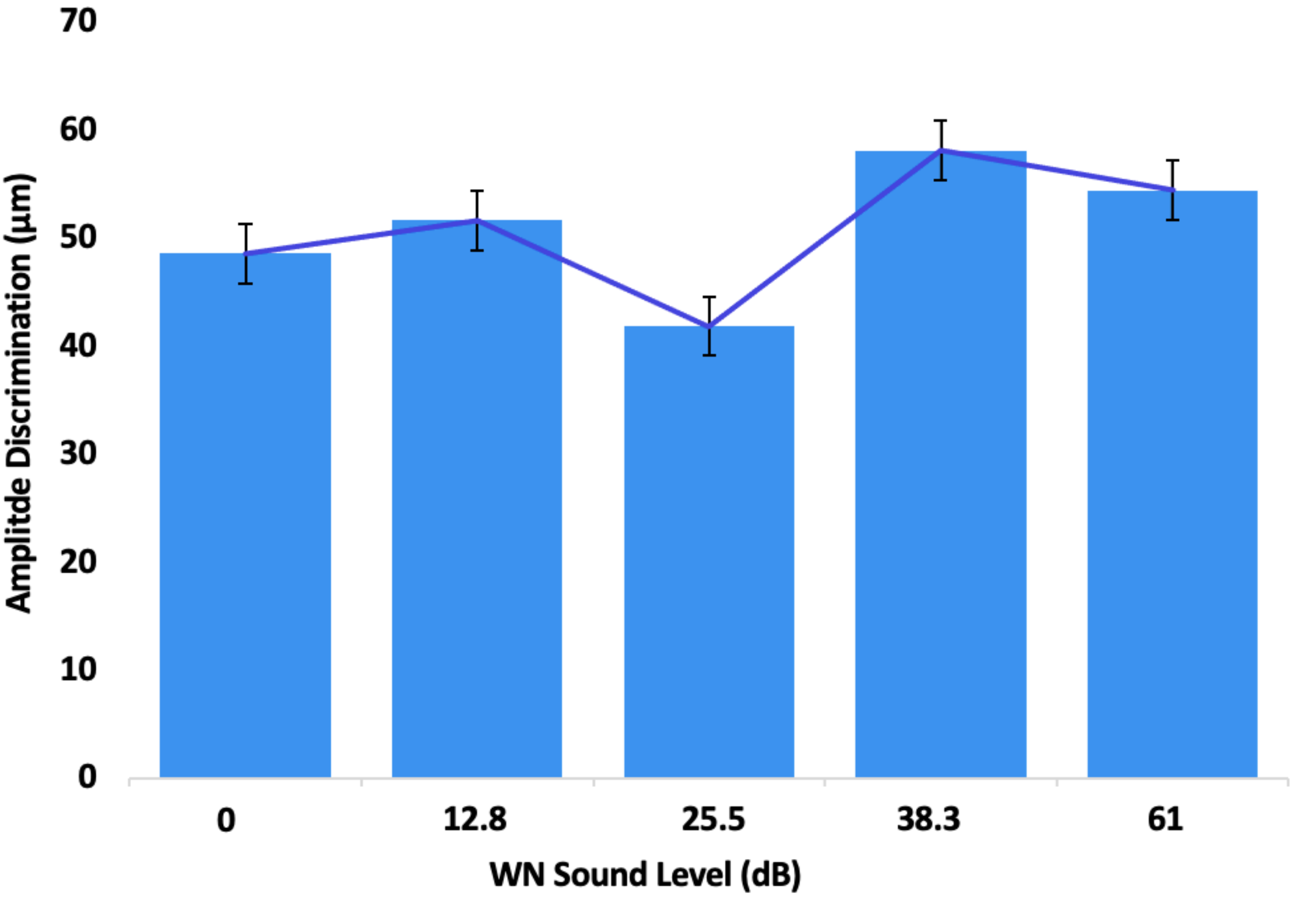

Figure 1. *Average amplitude discrimination scores resemble a U-shaped trend in the presence of increasing levels of WN.*

The graph exhibits the average amplitude discrimination scores of subjects at each sound level tested. Data was collected from 7 subjects and outlier scores were excluded. Error bars are standard error. No statistically significant differences were observed across the five sound levels of WN (two sample t-test assuming equal variances).

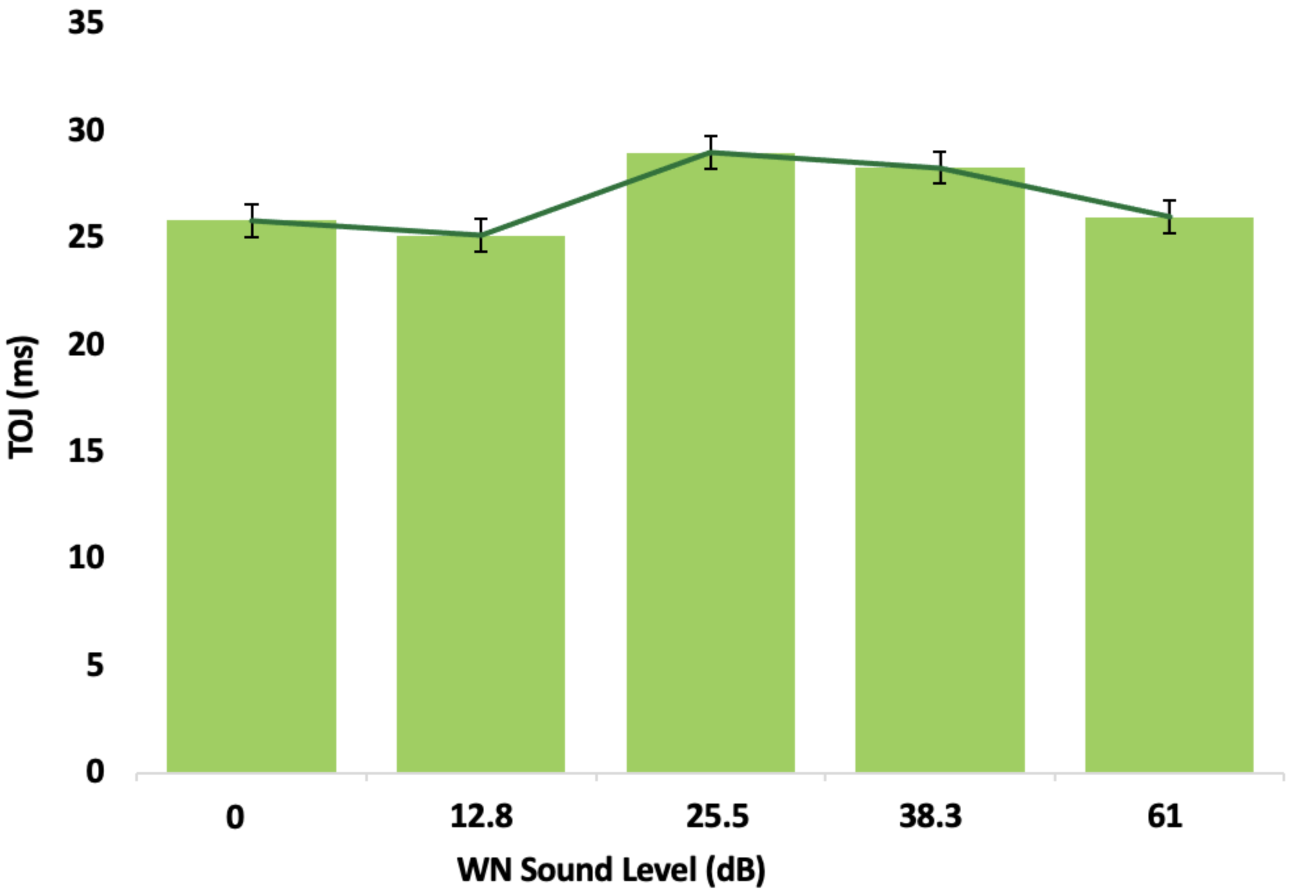

Figure 2. *Average temporal order judgement scores demonstrate that this task is unaffected by increasing levels of WN.*

The graph displays the average TOJ scores of subjects at each sound level tested.Data was collected from 7 subjects and outlier scores were excluded. Error bars are standard error. No statistically significant differences were observed across the five sound levels of WN (two sample t-test assuming equal variances).

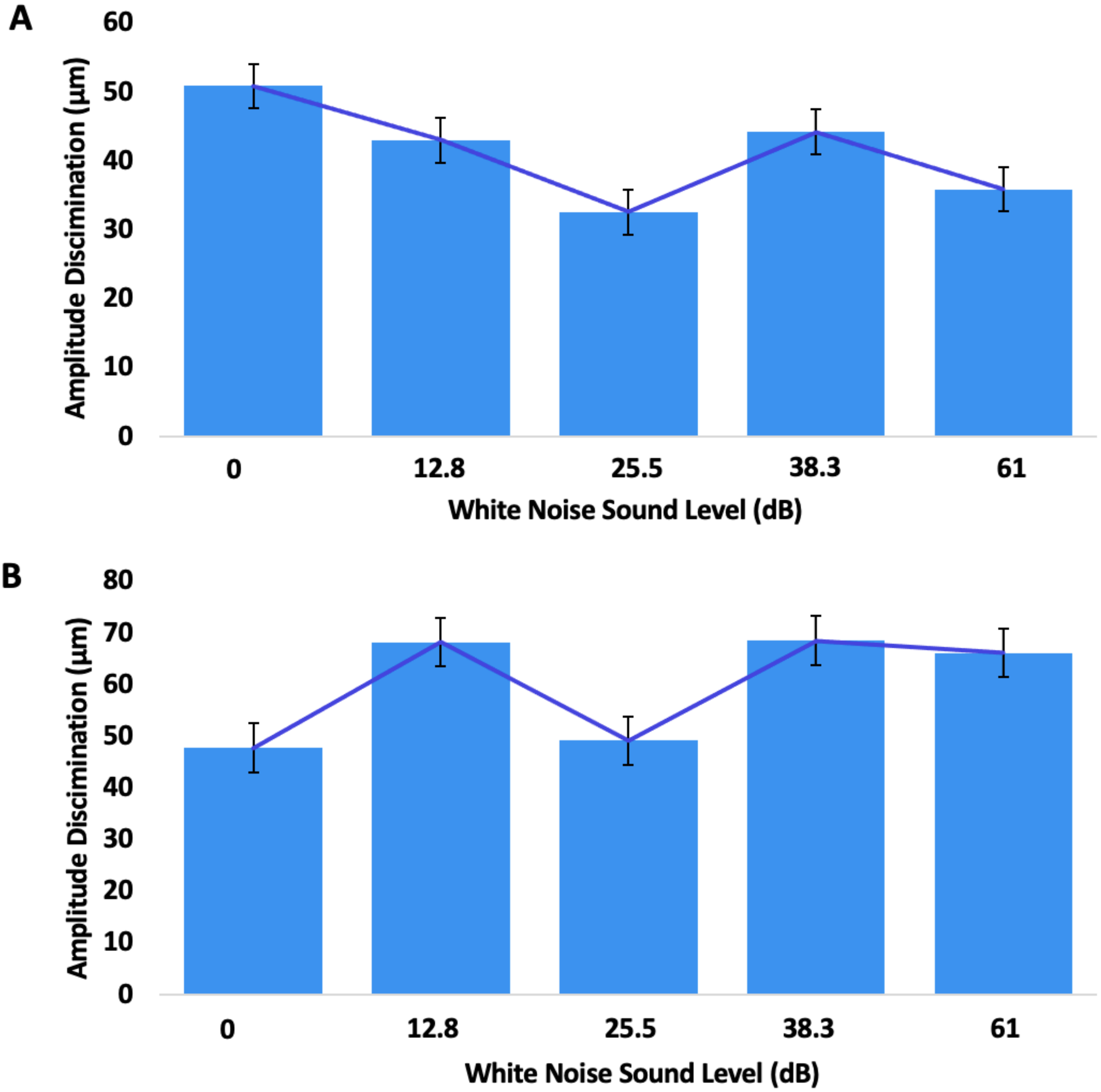

Figure 3. *Average amplitude discrimination scores of subjects with prior WN exposure demonstrate a pronounced U-shaped tuning curve in response to increasing levels of WN.*

The graphs exhibit average amplitude discrimination scores. Error bars are standard error. No statistically significant differences were observed across the five sound levels of WN (two sample t-test assuming equal variances). (A) Average amplitude discrimination scores of three participants with prior regular exposure to WN are displayed. Best cognitive performance occurred at 25.5 dB. (B) Average amplitude discrimination scores of four participants with no prior exposure to WN are displayed. Best cognitive performance occurred at 0 dB of WN.

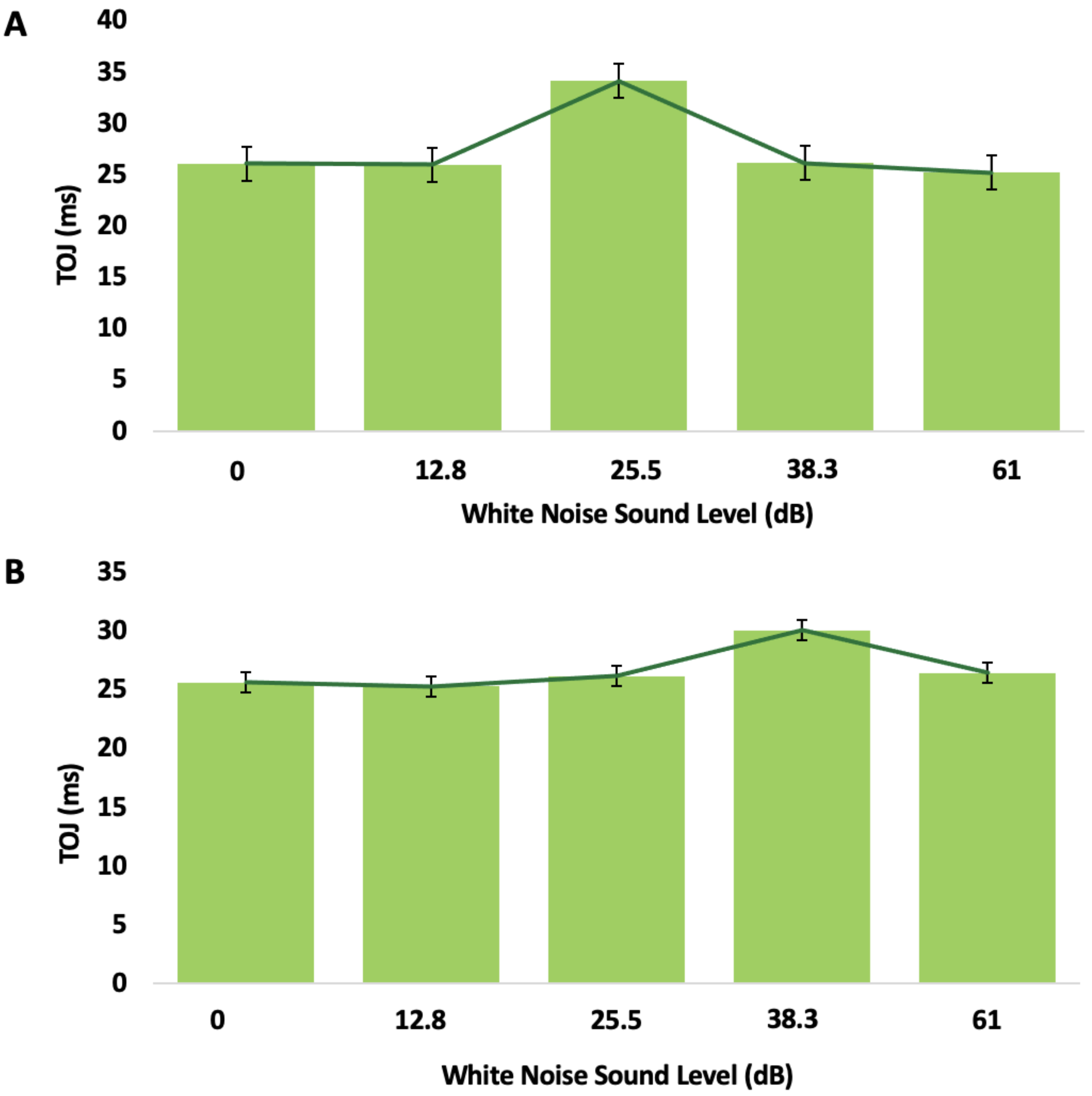

Figure 4. *Average TOJ scores of subjects with and without prior WN exposure demonstrate that this task is unaffected by increasing levels of WN.*

The graphs exhibit average TOJ scores. Error bars are standard error. No statistically significant differences were observed across the five sound levels of WN (two sample t-test assuming equal variances). (A) Average TOJ scores of three participants with prior regular exposure to WN are displayed. (B) Average TOJ scores of four participants with no prior exposure to WN are displayed.

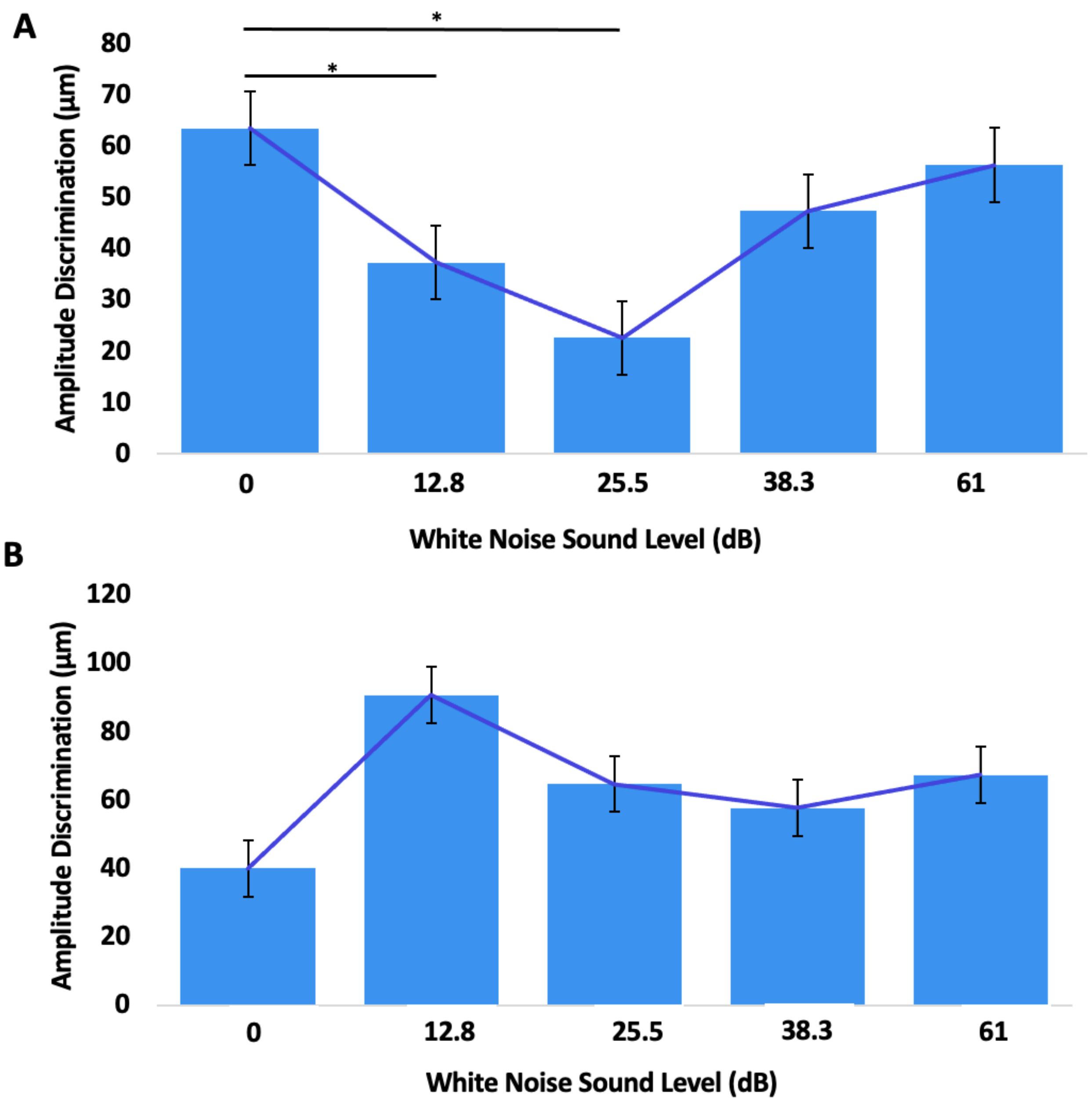

Figure 5. *Average amplitude discrimination scores for some individuals can elicit U-shaped tuning curves and significant differences in cognitive performance across increasing levels of WN.*

The graphs exhibit average amplitude discrimination scores for two individuals. Error bars are standard error. All significant differences with respect to 0 dB of WN in (A) and (B) are calculated with a two-sample t-test assuming equal variance indicated by $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). (A) Average amplitude discrimination scores of one participant with prior WN use are displayed. Significant differences in scores observed between 0 dB and 12.8 dB, and 0 dB and 25.5 dB. Best cognitive performance occurred at 25.5 dB. (B) Average amplitude discrimination scores of one participant with no prior exposure to WN are displayed. Best cognitive performance occurred at 0 dB of WN, and no significant differences were detected.

Results

Average amplitude discrimination scores resemble a U-shaped trend in the presence of increasing levels of WN.

Figure 1 displays the effects of different levels of WN on cognitive performance. Specifically, the average simultaneous amplitude discrimination score of all subjects (n=7) under different intensities of WN are displayed at 0, 12.8, 25.5, 38.3, and 61 dB. The authors hypothesized that participants would demonstrate a U-shaped tuning curve, demonstrating optimal performance at moderate sound levels and attenuated performance at too low or too high intensities of WN. Participant data displayed a shallow U-shaped tuning curve, indicating that WN intensity likely impacts cognitive performance (Figure 1). Optimal performance occurs at 25.5 dB and the worst performances occur at 38.3 dB, with 61 dB only displaying a slightly improved performance from that exhibited at 38.3 dB. Although the data depicts a U-shaped tuning curve and a clearly optimal performance at 25.5 dB, a two-sample t-test found no statistically significant differences were determined within this pool of participants (Figure 1). Thus, the initial hypothesis is partially supported. The U-shaped tuning curve indicates that WN impacts cognitive ability and that there is an optimal level of WN that can facilitate cognitive performance. However, the lack of statistical significance specifies that the initial hypothesis is not fully supported within the conditions of this study.

Average temporal order judgement scores demonstrate that this task is unaffected by increasing levels of WN .

The impact of differing levels of WN on TOJ performance is displayed in Figure 2. This figure displays the average TOJ performance of all subjects (n=7) while listening to 0 12.8, 25.5, 38.3, and 61 dB. The authors hypothesized that the participants would perform best at a moderate intensity of WN and worse at levels that are of a too high or too low intensity, presenting a U-shaped tuning curve. The data regarding TOJ does not display the expected U-shaped tuning curve of performance (Figure 2). WN appears to have little to no effect on TOJ performance. However, the participants do display a slight attenuation to performance at 25.5 and 38.3 dB. Optimal performance appears to occur at 12.8 dB. TOJ average scores were analyzed with a two-sample t-test which signaled no significant differences between any of the intensities of WN used. Thus, as well as the failure of the data to display a trend for the effect of WN on TOJ performance, statistics confirm that there are no differences that garner significance (Figure 2). Therefore, the authors' hypothesis was not supported by the data.

Average amplitude discrimination scores of subjects with prior WN exposure demonstrate a *pronounced U-shaped tuning curve in response to increasing levels of WN.*

Since there were differences observed in the overall average amplitude discrimination scores across varying levels of WN, the authors thought it important to investigate subjects that may have instigated the trend displayed in Figure 1. The authors hypothesized that subjects with previous regular exposure to WN (n=3) would demonstrate higher optimal WN levels at which cognitive performance was the best compared to those of subjects with little to no experience with WN (n=4). To test this hypothesis, the study compared the average amplitude discrimination scores of subjects who claimed to have regular exposure to WN to those who did not (Figure 3). Subjects with previous exposure to WN showed a more pronounced U-shaped tuning curve than that observed in Figure 1 (Figure 3 A). Although no significant differences were observed between the amplitude discrimination scores across the differing WN levels, there is a clear indication of a U-shaped tuning curve of cognitive performance (Figure 3 A). However, the only value that does not fall into the U-shaped trend is the average amplitude discrimination score measured at 61 dB. At approximately 36 dB, the average amplitude discrimination score was lower than what the trend would predict (Figure 3 A). The best cognitive performance, indicated by the lowest amplitude discrimination scores at approximately 32.6 □□m, was observed at the WN level of 25.5 dBFigure 3 A). This demonstrated that the level of WN to which these subjects were optimized to was 25.5 dB. For subjects with no previous exposure to WN, there seemed to be no clear trend of average amplitude discrimination scores across the varying levels of WN (Figure 3 B). In addition, there were no statistical differences observed across any of the different levels of WN (Figure 3B). The best cognitive performance occurred at 0 dB at approximately 47.8□□m, which could be thought of as the optimal level of WN for subjects with no experience with WN (Figure 3 B). These data from both Figure 3 A and Figure 3 B supported the hypothesis. The optimal sound level of WN for subjects with previous exposure to WN was determined to be higher than that of subjects with little to no experience with WN.

Average TOJ scores of subjects with and without prior WN exposure demonstrate that this task is unaffected by increasing levels of WN .

Just as it was done with the overall amplitude discrimination scores, average TOJ scores were calculated for both subjects with previous regular exposure to WN and those with little to no experience with WN (Figure 3). Though there was no trend observed in the overall average TOJ scores across the different WN sound levels, the authors decided to analyze this data further to confirm the conclusion from Figure 2––the TOJ task is not affected by differing levels of WN. The authors hypothesized that these two groups would demonstrate similar data––specifically, that there would be no clear trend correlating TOJ scores to differing levels of WN. The data exhibited that both groups of subjects demonstrated TOJ scores that appeared to not be affected by variation in WN levels (Figure 4). Additionally, both groups demonstrated their best cognitive performance at lower levels of WN––though, it should be noted that these values were not significantly different from any of the other average TOJ scores at different WN sound levels (Figure 4). Similar trends were observed in overall average TOJ scores, supporting the hypothesis (Figure 2). With this data combined with the data from Figure 2, it can be concluded that differing levels of WN indeed have no effect on the TOJ task.

Average amplitude discrimination scores for some individuals can elicit U-shaped tuning curves and significant differences in cognitive performance across increasing levels of WN .

In order to determine whether WN truly affected the individuals’ ability to perform on the amplitude discrimination task, this study investigated each subject’s individual amplitude discrimination scores across all of the WN sound levels tested. The authors hypothesized that subjects with prior exposure to WN would demonstrate data more analogous to a tuning curve as compared to subjects without experience with WN. One subject with previous regular exposure to WN demonstrated significantly lower average amplitude discrimination scores at both 12.8 dB ($p < 0.05$) and 25.5 dB ($p < 0.05$) of WN with respect to the amplitude discrimination score at 0 dB of WN (Figure 5 A). Furthermore, the amplitude discrimination score at 25.5 dB was the lowest across all WN levels and most statistically different from the average score at 0 dB (Figure 5 A). It could be concluded that this subject was optimized to a WN level of 25.5 dB––in other words, this subject demonstrated optimal cognitive performance at 25.5 dB of WN (Figure 5 A). The average amplitude discrimination scores of a representative subject with no previous exposure to WN was also analyzed (Figure 5 B). Just as seen in Figure 3 B, there was no obvious trend in their average amplitude discrimination scores across the differing sound levels of WN (Figure 5 B). Additionally, it appeared that this subject’s optimal cognitive performance occurred at 0 dB of WN––demonstrating that WN may have hindered their performance on the amplitude discrimination task (Figure 5 B). But it is important to note that there were no significant differences detected (Figure 5 B). The data from these two individuals supported authors’ hypothesis––the average amplitude discrimination scores across several levels of WN demonstrated a tuning curve in a representative participant who had previous experience with WN, while those of a subject with a lack of regular exposure to WN demonstrated no trend (Figure 5). Also, this data demonstrates that it is possible to elicit significant differences in amplitude discrimination with changes in WN and further, that WN can affect cognitive performance in general.

Discussion

This pilot study investigated the effects of auditory WN on cognitive performance. The authors hypothesized that the participants would demonstrate a U-shaped tuning curve of performance. Specifically, the authors predicted that the healthy adult participants' TOJ and simultaneous amplitude discrimination scores would be optimal while listening to moderate intensities of WN, and their worst scores would be witnessed when exposed to intensities of WN that are too low or too high. Upon analysis of average simultaneous amplitude discrimination and TOJ scores, the researchers found that participants displayed a U-shaped tuning curve for simultaneous amplitude discrimination performance, but not for TOJ. Further, participants presented an optimal level of amplitude discrimination performance at 25.5 dB. Although participants displayed a better performance at this level, this improvement was not statistically significant. After primary analysis of the data, participants were separated into two categories and conducted further analyses. Data for participants with prior regular exposure to WN formed one group, while the data of those who had not used WN previously were placed into another. This separation revealed that those with prior exposure to WN display a U-shaped curve with an optimal level of performance at 25.5 dB. The group that had not had prior exposure to WN did not display a pronounced U-shaped curve and showed optimal performance at 0 dB, indicating that WN did not improve their performances. For TOJ, neither group displayed a U-shaped tuning curve, indicating no effect of WN on TOJ performance for either group. The final analysis was conducted on two subjects, one from each category of prior WN experience. The subject that had prior exposure to WN displayed a pronounced U-shaped tuning curve, demonstrating optimal performance at 25.5 dB. However, they showed statistically significant improvements in performance at 12.8 and 25.5 dB. Overall, the authors conclude that the hypothesis regarding TOJ performance is not supported while the hypothesis regarding amplitude discrimination is partially supported by findings of this study.

The findings of this study indicate that WN only improves the cognitive performance of individuals under certain conditions, and that TOJ and simultaneous amplitude discrimination are not equally vulnerable to the SR effects induced by WN. The fact that participants who had prior exposure to WN displayed improved performance in a U-shaped function, while those with no prior exposure to WN did not, indicates that familiarity with WN moderates its effectiveness on cognitive improvement. It may be presumed that individuals with previous exposure to WN have acclimated to higher noise levels and that their actual cognitive performance has not improved. However, when performance on the amplitude discrimination task of both groups is compared at their optimal levels of WN––47.8 μm at 0 dB for individuals without previous exposure to WN and 32.6 μm at 25.5 dB for individuals with regular previous exposure to WN––then it appears that WN improves cognitive performance. Individuals with prior exposure to WN have demonstrated lower amplitude discrimination scores, and therefore, higher cognitive performance, than participants without previous exposure to WN. Additionally, those with prior experience listening to WN rated the level of distraction that WN elicited to be much lower than those who have not had prior exposure to WN (see **Supplemental Figure 1**). This implies that in order to experience the WN facilitated improvements on cognitive performance, one must become accustomed to WN, so the stimuli do not serve as a distractor.

In addition to differences between subjects, the data displayed differing effects of WN on TOJ and amplitude discrimination. The authors present possible reasons for this discrepancy. Although amplitude discrimination and TOJ both involve executive functioning in the frontal lobe, amplitude discrimination tasks executive functioning more heavily and these tests fundamentally require differing actions from participants. Amplitude discrimination asks participants to compare the intensities between two stimuli while TOJ requires participants to sequence two events and determine which pulse came first. Perhaps the differences in how these two tasks were impacted by the introduction of WN lies in the fact that WN does not impact all areas of cognition equally. Alternatively, it is known that TOJ tasks are much more vulnerable to the effects of repetition than amplitude discrimination. That is, participants are more likely to improve their TOJ performance with each trial than in amplitude discrimination tasks. The researchers randomized the trials of participants, so it is possible that the influence of repetition caused the effects of each level of WN to be indiscernible. Another potential reason for the differences seen in the results of these two tests could lie in differences in cell activation. Amplitude discrimination relies heavily on lateral inhibition in the parietal cortex, while TOJ does not. WN may serve to enhance the process of lateral inhibition, explaining why WN would be more effective in performance augmentation on amplitude discrimination than in TOJ. N-methyl-D-aspartate (NMDA) receptors are implicated in lateral inhibition. These receptors may not be adequately stimulated by vibrotactile stimulation in order to elicit potentiation. Therefore, a second stimulus, such as WN, may be required to facilitate sufficient excitation to induce potentiation. This would allow for the enhancement of lateral inhibition, and thus, a heightened ability to discriminate between two stimuli.

The findings of this study contribute valuable new information to the body of literature regarding the impact of WN on cognitive performance. Many past studies have focused on the use of WN to enhance cognitive performance in children with ADHD. The results of these studies determined that WN at intensities of approximately 70-80 dB are effective in improving cognitive performance from baseline. One promising study claimed that the introduction of WN was more effective in enhancing cognitive performance than the use of stimulant medication [13]. Two of the proposed mechanisms for the facilitation of cognitive improvement witnessed with the use of WN include SR and the MBA model. SR describes a phenomenon in which the introduction of additional noise into the neural system can facilitate cognitive performance [1]. This model predicts a U-shaped function of performance in which individuals perform best with moderate levels of noise and worst at levels of noise that are too intense or too mild [1]. The MBA model postulates that the addition of auxiliary neural noise is helpful because it increases dopamine function within the brain [7]. Thus, this explains why individuals with lower levels of dopamine, such as those with ADHD or those who are sub-attentive, benefit from the introduction of WN [4]. Although it has been definitively determined that WN is beneficial in those who are sub-attentive or diagnosed with ADHD, the literature provides contradictory evidence for the impact of WN on the cognitive performance of healthy adults with no cognitive or attentional deficits. Previous research has demonstrated that WN can have no effect on individuals with normal levels of attention and can be a detriment to the cognitive performance of super-attentive individuals, as well as a lack of a U-shaped curve of performance [4] . However, other research has shown that healthy adults’ performances can be enhanced by the use of WN and that they do display a U-shaped curve of performance [11].

This study provides preliminary evidence in support of the use of WN in healthy individuals to improve cognitive performance. The authors determined that under particular conditions, WN can be beneficial to the cognitive performance in adults with no cognitive or attentional deficits. findings refute previous research that claims that WN has no effects in healthy individuals. This study determined that individuals with prior exposure to WN display cognitive improvement on the amplitude discrimination task in a U-shaped fashion. However, due to the small sample size examined in this study, these results were not statistically significant. Further, the results provide preliminary support for the SR and MBA models in healthy adults. Results from the amplitude discrimination task indicate a shallow U-shaped trend, which became deeper when the data from participants with prior WN exposure were separated from the data of those who have not had prior exposure to WN. The findings of this study demonstrated dissimilar effects of WN on TOJ and amplitude discrimination tasks. Amplitude discrimination appeared to be impacted by the introduction of WN, while there was no clear impact of WN on TOJ performance. This provides support for previous research that concluded that not all facets of cognition are equally impacted by the use of WN, and provides further insight into what aspects of cognition are modulated by WN and which are not [16].

Though the results of this study are notable, it is important to take into account that there were some variations in the trends of cognitive performance across subjects with and without regular previous exposure to WN. Specifically, unexpected variation in TOJ scores was observed in overall averages for all participants, subjects with WN experience, and subjects without previous exposure to WN (Figures 2, and 4). Since performance on the TOJ task did not appear to be affected by increasing intensities of WN, all of the TOJ scores across these groups of participants should have been fairly consistent. Outside of some slight variation, this was almost entirely seen because there were no significant differences discerned in the TOJ data sets. Additionally, slight variation was also observed in overall average amplitude discrimination scores and those of subjects with regular previous exposure to WN (Figures 1, and 3 A). Particularly, participants with previous exposure to WN demonstrated data analogous to a U-shaped tuning curve (Figure 3 A). However, the amplitude discrimination averages at 0 dB and 61 dB were lower than projected for a solidified tuning curve (Figure 3 A). Lastly, slight variation was observed in the participant representative of subjects with no regular previous exposure to WN (Figure 5 B). This individual was optimized to a WN level of 0 dB, signifying that WN could potentially attenuate cognitive performance. If WN served to hinder performance in this individual, then there should have been a steady increase in amplitude discrimination with an increase in intensity of noise. This was not observed, rather, there were not any significant differences discerned across the different WN sound levels (Figure 5 B). Variations in the aforementioned data could be attributed to some confounding variables present in the study.

A confounding variable that could have affected the results is that participants could have taken the tests in differing visual environments. Depending on how distracting the visual environment in which the tests were taken, this could have been a factor contributing to the unexpected variation observed in the data. Furthermore, subjects could have taken the brain gauge tests at different times of day, leading to differences in fatigue. Another variable that could have potentially affected the results is differing tactile sensitivity across subjects. Since the tasks are designed to incorporated vibrotactile stimulation, tactile sensitivity greatly affected results. In addition to having different lifestyles, these subjects varied in age and gender, which could all have affected tactile acuity. In turn, this variation could have been reflected in the results. Lastly, continued practice with the vibrotactile tests could have caused unforeseen improvement in scores. Due to the repetitiveness of the experimental design––all seven subjects were naive to the brain gauge but took each task fifteen times––practice could have reduced the impact of stress and anxiety of completing a new task.

The effect of these confounding variables could be minimized by optimizing conditions across all participants. This would include testing in a consistent environment, such as performing the experimental procedure at the same time and place. Furthermore, when repeating this experiment, it could involve more subjects. Since the current study only involved seven subjects, this small sample size could have promoted bias in the results. For example, participants in this study were disproportionately female and all subjects were of similar socioeconomic backgrounds, which could skew the results. Incorporating a higher number of subjects that are of differing ages, races, genders and socioeconomic backgrounds would not only allow less bias to affect the results, but also it would be more generalizable to the entire neurotypical population.

Along with these changes, future studies could advance this research by focusing on specific ideas related to this pilot study. Alternative experimental designs that could further illuminate the effects of WN include utilizing a binary test to quantify the effects of WN on cognitive performance or drawing comparisons between the cognitive performance of high performing and low performing subjects. Additionally, a variation of tasks could be used to measure cognitive performance. For instance, the Simon task could be employed to measure the effect of WN on working memory, an aspect of cognitive ability. A future study could provide a more in-depth analysis of individuals who have had regular WN exposure. Specifically, it could focus on the query of whether the addition of WN actually boosts cognitive function or if the effects observed in this study are due to habituation. An example of another experiment that could further elucidate the effects of WN is conducting a longitudinal study on a few individuals who have never been exposed to WN before. In this longitudinal experimental design, the cognitive performance of participants would be measured without the addition of task-irrelevant noise over a specific period of time. Over the next few weeks, an increasing intensity of WN would be presented along with the tasks. This experiment would determine whether it is beneficial to introduce WN into the daily life of an individual of the neurotypical population.

Keeping these advancements in mind, this pilot study was among the first to explore the effects of

WN on healthy individuals who were representative of the neurotypical population. The results of this study emphasized that there is a possibility that WN could promote higher levels of cognitive performance, though there is likely an adjustment period associated with its introduction to daily life. This warrants that additional research must be conducted in order to cultivate a definitive conclusion about the effects of WN. However, this pilot study facilitated the first step in the process of characterizing a method that could potentially augment cognitive ability in neurotypical individuals.

Supplemental Figures

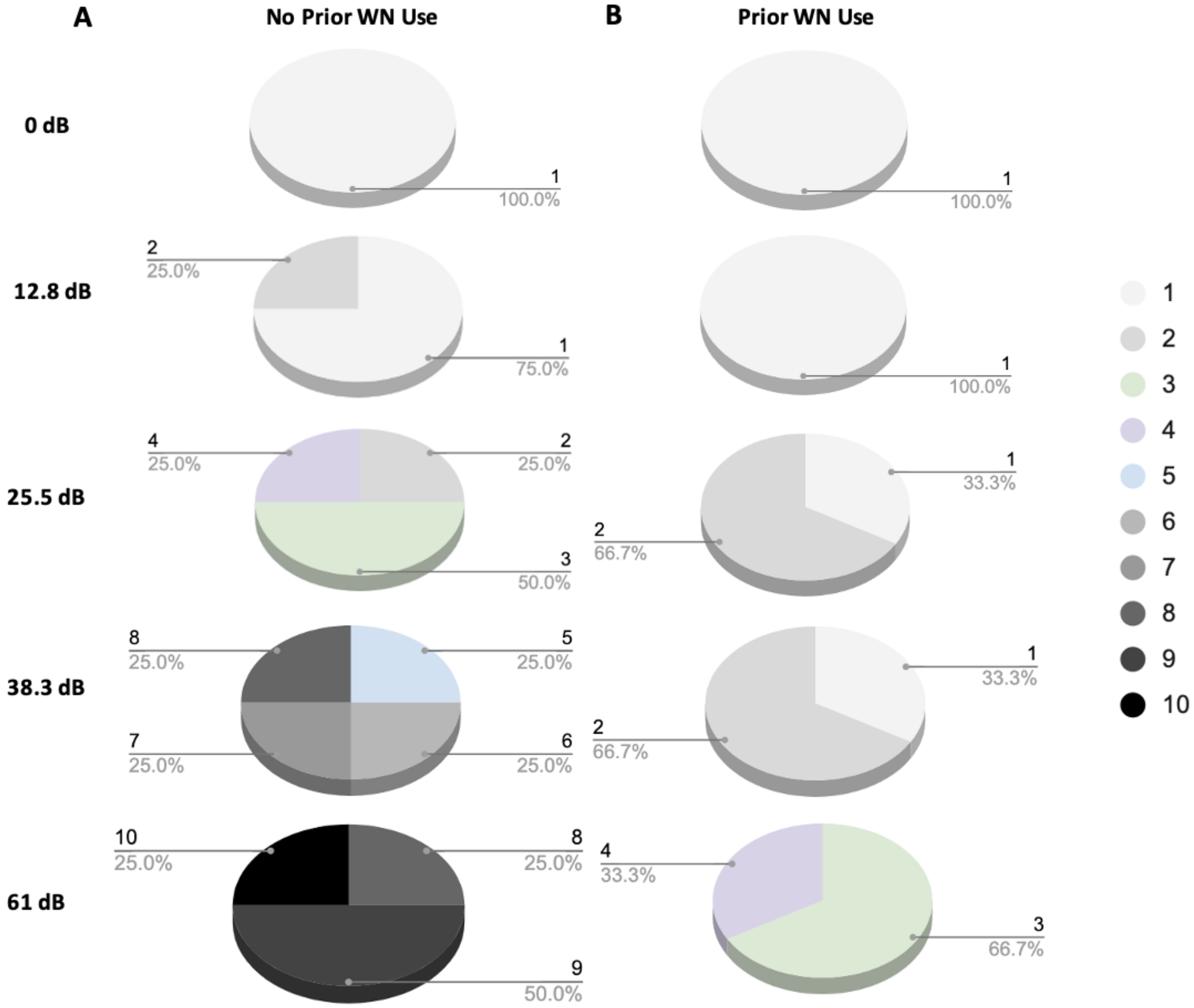

Figure 6. *Participants with prior WN experience report lower levels of distraction than those with no experience.*

Participants were asked to rate how distracting they found the auditory stimuli at each intensity on a 10-point scale (1 = not distracting at all, 10 = extremely distracting). Legend displayed to the right. (A) Ratings of participants who have had no past exposure to WN. (B) Ratings of participants who have had regular prior WN exposure.

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