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White noise facilitates new-word learning from context

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ABSTRACT

Listening to white noise may facilitate cognitive performance, including new word learning, for some individuals. This study investigated whether auditory white noise facilitates the learning of novel written words from context in healthy young adults. Sixty-nine participants were required to determine the meaning of novel words placed within sentence contexts during a silent reading task. Learning was performed either with or without white noise, and recognition of novel word meanings was tested immediately after learning and after a short delay. Immediate recognition accuracy for learned novel word meanings was higher in the noise group relative to the no noise group, however this effect was no longer evident at the delayed recognition test. These findings suggest that white noise has the capacity to facilitate meaning acquisition from context, however further research is needed to clarify its capacity to improve longer-term retention of meaning.

1. Introduction

The facilitation of signal processing via the addition of an optimal level of noise is referred to as stochastic resonance (SR) or stochastic facilitation (McDonnell & Ward, 2011). The concept of SR refers to a phenomenon whereby the addition of random noise can facilitate detection of a weak or subthreshold signal within a non-linear system (Moss, Ward, & Sannita, 2004). Moreover, while an optimal amount of noise can facilitate detection, increasing the noise intensity beyond that optimal level will result in a degradation of signal processing. More recently, SR has been the subject of many theoretical modelling and experimental studies, including within the neurosciences (McDonnell & Ward, 2011). One source of noise known to elicit SR is auditory white noise. White noise has been shown to enhance sensitivity not only to weak auditory signals (Zeng, Fu, & Morse, 2000), but also to cross-modal weak tactile or visual signals (Lugo, Doti, & Faubert, 2008; Manjarrez, Mendez, Martineza, Flores, & Mirasso, 2007).

White noise can also potentially facilitate cognitive processing. Whilst research suggests that white noise does not induce a generalized improvement to all aspects of cognition, and may even impair performance under some circumstances (Herweg & Bunzeck, 2015), white noise has been shown to improve some aspects of performance such as the speed of arithmetic calculations (Usher & Feingold, 2000). Some research also suggests that the effects of white noise may be mediated by attentional capacity. For instance, white noise has been shown to improve some aspects of cognitive performance in children with attention deficit hyperactivity disorder (ADHD) and in typically developing children rated by their teachers as being less attentive (Helps, Bamford, Sonuga-Barke, & Soderlund, 2014; Soderlund, Sikstrom, & Smart, 2007; Soderlund, Sikstrom, Loftesnes, & Sonuga-Barke, 2010), but to worsen cognitive performance in children with higher levels of attention (Helps et al., 2014; Soderlund et al., 2010).

Such findings may be consistent, at least partially, with the moderate brain arousal (MBA) model (Sikstrom & Soderlund, 2007). Similar to the Yerkes-Dodson model, which postulates an inverted U shaped function between performance and arousal (Yerkes & Dodson, 1908),

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the MBA model suggests that a moderate level of neural noise (i.e., background neural activity) is required for optimal brain function. The model further suggests that this neural noise is modulated through the dopamine system, such that when tonic dopamine levels are low, there is insufficient neural noise for optimal cognitive performance. A critical aspect of the MBA model is the assumption that adding external noise through the perceptual system (e.g., auditory white noise), can compensate for the effects of lower dopamine by introducing internal noise into the neural system, thereby facilitating cognitive performance.

Sikstrom and Soderlund (2007) use the example of attention deficit hyperactivity disorder (ADHD) to illustrate the MBA model. They propose that due to reduced extracellular dopamine levels (and hence lower neural noise) in individuals with ADHD, more external noise is required to achieve higher cognitive performance. In contrast, people with normal attention/dopamine levels are expected to require less external noise for optimal cognitive performance.

Rausch, Bauch, and Bunzeck (2014) explored the neural mechanisms that underpin the effects of white noise on learning using functional MRI, and found that presenting white noise during the encoding of scene images decreased sustained activity and increased event-related activity within the substantia nigra and ventral tegmental area, and increased functional connectivity between those regions and the superior temporal sulcus. Moreover, memory improvements in white noise were positively correlated with right superior temporal sulcus activity. Rausch et al. suggested that enhanced phasic dopamine release in response to white noise could modulate activity within the superior temporal sulcus, thereby increasing attention and memory formation. Such findings contribute to mounting evidence that white noise could improve cognitive performance via dopaminergic mechanisms.

Following reports that levodopa (an exogenous dopamine precursor) had been shown to improve new word learning in healthy adults (Breitenstein et al., 2006; Knecht et al., 2004; Shellshear et al., 2015), Angwin et al. (2017) showed that similar effects could be achieved using white noise. After showing improved word recall in participants who listened to white noise during the learning phase of a word learning task relative to participants who had learned the words in silence, Angwin et al. speculated that white noise might have increased phasic dopamine activity, thereby facilitating attention and enhancing the salience of stimuli during learning. These authors also speculated that white noise may have enhanced hippocampal-dependent memory formation due to the effects of white noise on activity within the ventral tegmental area. While Angwin et al. (2017) showed white noise improved new word learning in healthy adults, these results were not affected by executive attention. This was in contrast to Angwin et al. (2018) who, in a similar population of healthy adults, later showed that white noise focused semantic activation (as evidenced by a reduction in indirect semantic priming), particularly in those with lower attention.

Angwin et al. (2017) employed a word learning paradigm that involved repeated presentations of picture/word pairs. Such a procedure has limited resemblance to the manner in which language is typically learned, however it is recognized that word learning can occur from context during natural reading (Nagy, Anderson, & Herman, 1987; Nagy, Herman, & Anderson, 1985). Approaches that examine new word learning from a linguistic context could offer a more naturalistic investigation of lexical acquisition. Mestres-Missé, Rodriguez-Fornells, and Münte (2007) provided an example of this approach, investigating new word learning in healthy adults by presenting novel words within sentence triplets where contextual constraint increased across the three sentences. In a congruent condition, all three sentences led to a consistent meaning, allowing participants to determine the meaning of the novel word. In an incongruent condition, the sentence contexts were inconsistent such that no meaning for the novel word could be derived. The authors measured electro-encephalography during task performance and found that by the third sentence, event-related potentials (ERPs) for novel words in the congruent condition were similar to those obtained for familiar words, providing an indication of the rapid acquisition of meaning from sentence context.

Using fMRI, Mestres-Missé, Camara, Rodriguez-Fornells, Rotte, and Münte (2008) found that contextual word learning was associated with activity across a distributed network including the left inferior frontal gyrus, the medial temporal gyrus, the parahippocampal gyrus, the thalamus and striatum. Subsequent research using a similar paradigm has provided further insights into the neural mechanisms that underpin this form of word learning. Ripollés et al. (2016) observed enhanced activity within a dopaminergic network involving the ventral striatum, the substantia-nigra/ventral tegmental area (SN/VTA) and the hippocampus for successful new word learning. The authors suggested that this network may modulate the entrance of new words into long term memory via dopaminergic modulation of the midbrain. In a recent pharmacological study using the same task, Ripollés et al. (2018) provided causal evidence for a dopamine-dependent mechanism instrumental to this type of learning: a dopaminergic precursor (levodopa) and a dopamine receptor antagonist (risperidone) increased and decreased, respectively, measures of contextual new word learning.

Accordingly, the present study sought to extend upon previous findings that white noise enhances ‘associative’ word learning in healthy adults (Angwin et al., 2017), to explore whether such effects translate to more naturalistic ‘contextual word learning’ in healthy adults. Given white noise has been shown to engage a dopaminergic network involving the SN/VTA during non-linguistic learning (Rausch et al., 2014), and that contextual word learning engages a similar network (Ripollés et al., 2016), it was hypothesized that learning would be improved in white noise relative to silence both immediately after learning, as well as at a delayed follow-up. It was further hypothesized that this effect would be mediated by executive attention capacity, given previous evidence that the effects of white noise on semantic processing are mediated by attention (Angwin et al., 2018).

2. Methods

2.1. Participants

Ninety undergraduate students participated in the research for course credit. Twenty participants were ineligible for study inclusion because they reported a hearing loss (n = 1), non-corrected vision (n = 1), English as a second language (n = 12) or a history of depression and/or were taking anti-depressant medication (n = 6). One participant also ceased participation due to illness on the day of testing. Accordingly, 69 participants were included in the study, with 66 reporting as right handed and 3 as left handed. Thirty-three participants (31 female, 20.6 ± 1.0 years of age, 15.0 ± 0.9 years of education) completed the learning phase of the task while listening to white noise and the remaining 36 participants (35 female, 22.8 ± 5.4 years of age, 15.7 ± 1.7 years of education) completed the task without noise. The groups were not significantly different in age ($p = 0.95$) or years of education ($p = 0.33$). The study was approved by the human research ethics committee of the University of Queensland and all participants provided written informed consent prior to participation.

2.2. Word learning task

2.2.1. Stimuli

The paradigm was similar to previous contextual word learning research using low and high constraint sentence pairs as stimuli (Ripollés et al., 2017, 2018, 2016, 2014). Stimuli consisted of 40 sentence pairs and 40 nonword targets. Twenty of the nonwords were randomly assigned to a ‘congruent’ (M+) condition and 20 were assigned to an ‘incongruent’ (M−) condition. The assignment of items to these conditions was the same for all participants. In the M+ condition, the sentence pair led to a consistent meaning of the nonword (e.g., Dick waited to read a balen; Dick wrote a chapter in the balen). In the M- condition, the two sentences led to different meanings (e.g., They took short trips during the bonaf; Father carved a turkey with a bonaf).

The nonword targets, selected from Gupta et al. (2004), were all two syllables in length and followed regular English spelling rules (e.g., balen). The sentences were each 5–7 words long and selected from sentence cloze norms (Bloom & Fischler, 1980). Two of the original sentences were adjusted (single word substitution) in order to be culturally relevant while retaining the original meaning. The first sentence of each pair always had low cloze probability (mean of 19%) and the second sentence had high cloze probability (mean of 83%) based on the Bloom and Fischler (1980) normative data.

To confirm that the cloze probability of the M+ sentence pairs was high when read sequentially in this manner (i.e., low cloze followed by high cloze sentence), 15 healthy adults not participating in the experimental study read the 20 sentence pairs and provided the word that best completed each pair. Results demonstrated that the sentence pairs used for the M+ condition had high cloze probability (91.2%).

The entire list of 40 sentence pairs (20 M+ and 20 M−) was divided into 5 blocks of trials, each consisting of 4 M+ and 4 M− trials. The order of the trials within a block was randomized for each participant.

2.2.2. Procedure

The task consisted of a learning phase followed by two recognition phases. Initial pilot testing revealed that participants struggled to learn word meanings when the low/high constraint sentence pairs were not presented consecutively during learning. Thus, during the learning phase, each trial consisted of two consecutively presented sentences of the same condition (M+ or M−), followed by the same nonword (Fig. 1; Mestres-Missé et al. (2007)). In this way, participants saw each nonword twice (once at the end of each sentence). Participants were asked to learn the meaning of the nonwords that followed sentence pairs with a congruent meaning (M+ condition), and to reject the meaning of nonwords that followed sentence pairs with an incongruent meaning (M− condition). To verify that participants had correctly identified or rejected each novel word meaning, they were asked at the end of each trial to type the meaning of the nonword or to press the 'x' key if they had rejected the meaning. The learning phase was completed across 5 blocks of trials, each 2–3 min in duration, with allowance of a short break between blocks.

After completing the learning phase, all participants immediately completed a recognition test phase. On each trial, a nonword from the learning phase was presented with two possible meanings below it, one on the left and one on the right. When the nonword was from the M+ condition, one meaning was the correct meaning for that word, and the other was a meaning relating to a different sentence used within the experiment. In the case of a nonword from the M- condition, one meaning related to the second sentence presented with that particular nonword during learning, and the other meaning related to a different sentence used within the experiment. Participants were asked to use the left and right arrow keys to select the correct meaning for the nonword (i.e., if the participant had learned a meaning for the nonword [M+ condition]), or to press the spacebar to indicate that the nonword had no meaning (i.e., the nonword was from the incongruent, M− condition). The next trial began after the participant's response or after 5 s, whichever came first. After approximately 20 min, in which the participants completed an unrelated task, the participants completed the same recognition test again. The order of stimulus presentation within each recognition test was randomized separately for every participant.

The learning and recognition tests were presented using E-Prime 2.0 (Psychology software tools Pittsburgh, PA, USA). Participants assigned to the noise group completed the learning phase of the task while listening to white noise (monotrack, 44,100 Hz sampling frequency with 32-bit float), which was generated using Audacity software (bandwidth 86 Hz–22.007 kHz) and delivered at 70 dB SPL(A) via AKG closed back reference class headphones. All participants completed the recognition phases without noise.

2.3. Attention test

On a separate day, participants completed a modified version of the Attention Network Test (ANT) (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Each trial consisted of a central arrow, pointing left or right, surrounded by flanking arrows pointing in either the same (congruent) or the opposite (incongruent) direction. Different cues preceded the target on some trials, and participants identified the direction of the central arrow as quickly and accurately as possible via button press. Of interest in the present study was the executive control (conflict) effect score, which is calculated by subtracting the mean reaction time for congruent trials from the mean reaction time for incongruent trials (only trials with a correct response are included in this calculation). This measure provides an indication of the efficiency of the executive control network, such that the executive control of attention is lower in those people with a larger score.

The task consisted of three blocks of 48 randomized trials, with short rest breaks provided to participants after each block. Participants also completed a short practice task prior to beginning the experiment, with feedback on both reaction time and accuracy provided. No feedback was provided during the test proper and the task was presented

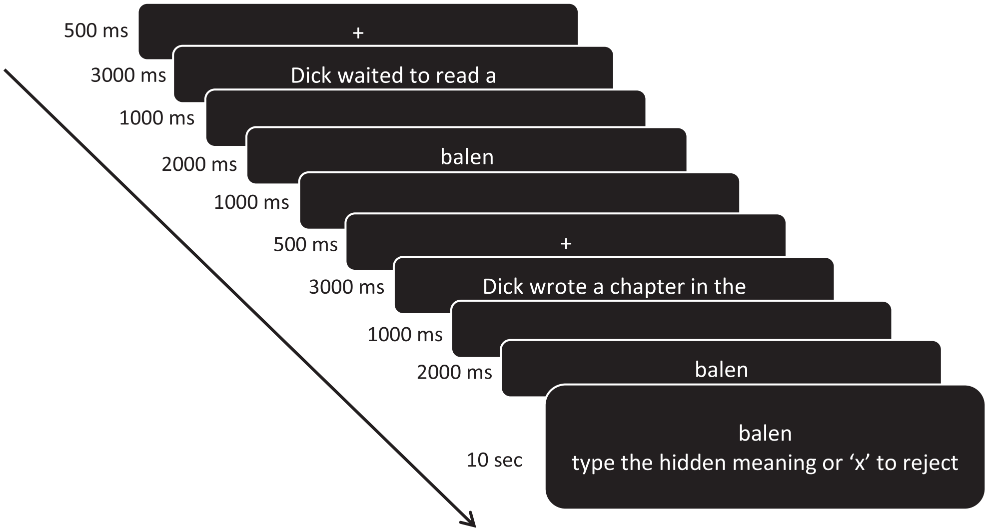

Fig. 1. Illustration of a trial during the learning task.

using E-prime 2.0.

2.4. Statistical analyses

All statistical analyses were performed using SPSS (Chicago, IL), version 25 for Windows, and the data were inspected for normality prior to statistical analysis by examining skewness and kurtosis. Independent samples *t*-tests were used to compare proportion accuracy between groups. These tests were conducted separately for each condition (M+/M−) as the conditions measure different constructs. Specifically, recognition for the M+ condition measures meaning construction from context, whereas recognition for the M- condition measures the detection of meaning incongruency. Similarly, *t*-tests were also performed separately for the immediate and delayed recognition tasks, consistent with previous research (Ripollés et al., 2016). A bonferroni adjustment was applied to account for these multiple tests of recognition accuracy, which changed α to 0.0125 for these comparisons. Pearson's R analyses were subsequently used to examine whether learning performance for either condition was associated with executive attention skills as measured by the ANT (Fan et al., 2002).

3. Results

3.1. Learning phase

The proportion of correct answers for each condition was the dependent variable of interest. For the M+ condition, an answer was correct when a participant provided an appropriate meaning for the novel word based upon the sentence pair context, whereas for the M− condition, an answer was correct whenever a participant identified (by pressing 'X') that a sentence pair led to no consistent meaning. Skewness and kurtosis for the proportion accuracy data were within ± 1.5 for each group and condition. These data were compared between groups (noise/silence) using independent samples *t*-tests, conducted separately for the M− and M+ conditions.

The analysis of the M+ condition showed no significant difference in proportion accuracy between groups (Silence 0.66 [SD 0.09]; Noise 0.67 [SD 0.12]; $p = .775$, $d = 0.09$). Errors for the M+ condition during the learning phase were predominantly cases where participants incorrectly rejected the sentence pair as having no meaning (24.15% and 19.35% of trials for the Silence and Noise groups respectively) or assigned a meaning to the sentence pair that was incongruent with the meaning of both sentences (9.05% and 12.85% of trials for the Silence and Noise groups respectively). Similarly, analysis of the M- condition revealed no significant difference in proportion accuracy between groups, with performance near ceiling for both groups (Silence 0.98 [SD 0.04]; Noise 0.96 [SD 0.05]; $p = .129$; $d = 0.44$).

3.2. Recognition tests

For each individual participant, recognition accuracy was calculated based only on the items that were responded to correctly during the learning phase. Accordingly, and as per the data presented in Section 3.1, the mean number of trials used to calculate proportion accuracy was similar for each group (Silence group, 13.25 trials for M+ and 19.50 trials for M−; Noise group, 13.40 trials for M+ and 19.17 trials for M−). These proportion accuracy data (Fig. 2) were subsequently compared between groups (noise/silence) using independent samples *t*-tests.

3.2.1. Immediate recognition

For the immediate recognition data, skewness was within ± 0.5 and kurtosis within ± 1.1 for each group and condition. An independent samples *t*-test revealed that recognition accuracy for the M+ condition was significantly higher for the Noise group relative to the Silence group, $t(64) = 3.27$, $p = .002$, $d = 0.83$ (Noise = 0.67, Silence = 0.55; Fig. 2). In contrast, there was no significant difference between groups for the M- condition (Noise = 0.47, Silence = 0.54, $p = .159$, $d = 0.35$).

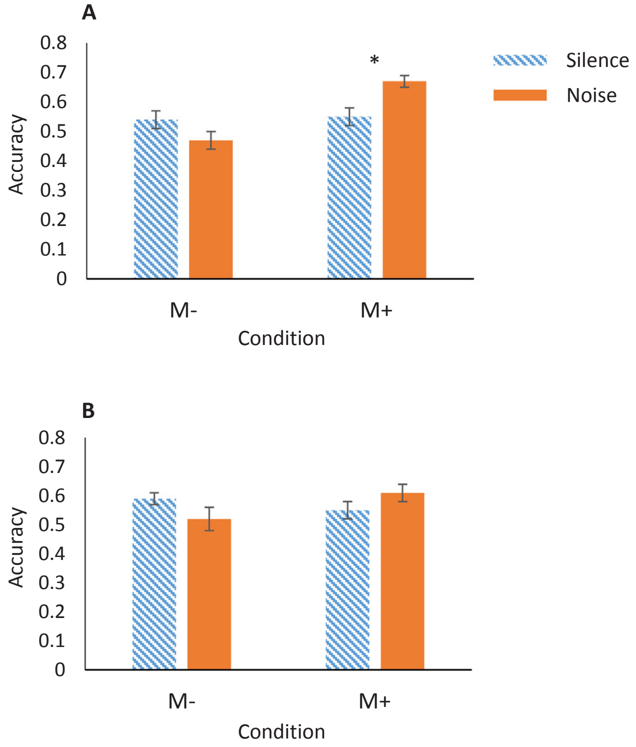

Fig. 2. Mean proportion accuracy for each condition and group at (A) the immediate recognition test, and (B) the delayed recognition test. Standard error bars provided. Significantly higher accuracy ($p < .01$) for the noise group relative to the silence group at the immediate recognition test (as indicated by *).

3.2.2. Delayed recognition

For the delayed recognition data (Fig. 2), skewness and kurtosis were within ± 1.0 for each group and condition. Independent samples *t*-tests revealed no significant difference in recognition accuracy between groups for either the M− condition (Noise = 0.52, Silence = 0.59, $p = .123$, $d = 0.38$) or the M+ condition (Noise = 0.61, Silence = 0.55, $p = .101$, $d = 0.36$).

3.3. The role of executive attention

In order to determine whether the effect of noise on learning was modulated by executive attention, the ANT executive control network score was calculated for each participant. This score was calculated by subtracting the mean reaction time for congruent trials from the mean reaction time for incongruent trials on the ANT. Two participants' data were excluded from these calculations due to a high error rate (> 85%) on the incongruent condition, which compromised the calculation of the attention score for those participants and suggested that they did not attend to the task instructions properly. *t*-tests on the remaining data confirmed that the executive control score did not differ significantly between the Noise and Silence groups (Silence, 81 ms (SD 46); Noise, 93 ms (SD 28); $p = .207$, $d = 0.32$).

For each group, Pearson's R correlations were then performed between the ANT executive network score and the proportion accuracy data at both immediate and delayed recognition for each condition (M−/M+). No correlations with executive attention were evident for either group.

4. Discussion

This study investigated the impact of white noise on novel word learning from context. It was hypothesized that white noise would facilitate learning relative to silence, and that this effect would be mediated by executive attention skills. The results partially supported these hypotheses.

Participants who completed the learning phase while listening to white noise showed significantly more accurate recognition of learned word meanings (M+ condition) immediately post task relative to those who completed learning in silence. Accordingly, the results add to existing evidence that white noise can facilitate language learning (Angwin et al., 2017), and extend the findings to a more naturalistic, contextual word learning paradigm. The beneficial effects of white noise appear consistent with the MBA model (Sikstrom & Soderlund, 2007), such that the provision of white noise boosts internal neural noise via the perceptual system, thereby improving cognitive performance. When considering the cognitive mechanisms that may actually be enhanced by white noise, a likely candidate relates to intrinsic reward-related processes. Ripollés et al. (2016) found that successful acquisition of word meanings from a similar contextual word learning task was associated with increased reward processing. The researchers proposed that intrinsic rewards, triggered by internal self-monitoring of correct performance, enhance memory formation. In a similar manner, we tentatively propose that white noise increased the salience of the learning outcomes associated with the task, such that participants derived greater reward and satisfaction from learning. It is also feasible to consider that white noise may directly facilitate attention and memory related processes, potentially whilst simultaneously driving reward-related mechanisms.

Turning to the potential neural mechanisms underpinning the effects of white noise on learning, there is substantial evidence to suggest that dopaminergic mechanisms may be responsible. Ripollés et al. (2016) found that enhanced signaling within the SN/VTA-VS-hippocampal loop was associated with successful learning of new words during a similar contextual word learning task. Moreover, activation within this network was not observed for the M- condition, suggesting that only meaningful learning in the M+ condition triggered activation of these regions. This was further supported in a recent pharmacological study, which showed that manipulating dopaminergic signaling (using levodopa and risperidone) affected reward and learning measures for the M+, but not for the M− condition (Ripollés et al., 2018). If white noise drives activation of a similar network, then improvements to recognition accuracy for the M+ condition but not the M− condition would be expected. Indeed, this is precisely what the results of the present study demonstrated. We acknowledge, however, that this proposal is speculative and requires neuroimaging research for verification.

There is also evidence to suggest that white noise might drive dopaminergic mechanisms relating to memory. Rausch et al. (2014) suggested that white noise might increase phasic dopamine release, which can improve stimulus salience and enhance encoding and memory formation. Similarly, within the context of the present study, increased phasic dopamine release when listening to white noise could increase the salience of, and attention towards, the sentence stimuli, thereby driving memory formation. Angwin et al. (2017) also speculated that white noise could drive hippocampal-dependent memory formation. The hippocampus receives dopaminergic input from a number of sources, including the VTA, which can contribute to hippocampal-dependent memories (Lisman & Grace, 2005; McNamara, Tejero-Cantero, Trouche, Campo-Urriza, & Dupret, 2014), and white noise has been shown to modulate activity within the VTA (Rausch et al., 2014). Further, the synchronization of left hippocampal activity as well as ipsilateral association areas has been linked to word learning success in healthy adults (Breitenstein et al., 2005). Thus, the facilitation of such neural mechanisms may underpin the improvements observed during white noise.

Of interest, analysis of the delayed recognition task did not provide the same pattern of results, with no significant difference between groups for either the M− or the M+ condition. This result suggests that the beneficial effects of white noise on contextual word learning decrease over time, which contrasts with findings that levodopa-induced improvements to novel word learning are maintained longer term (Breitenstein et al., 2006; Knecht et al., 2004; Shellshear et al., 2015). In considering such contrasting effects, task differences need to be acknowledged. Specifically, the drug studies have involved levodopa administration at each of five consecutive learning sessions, providing a substantially larger dose of dopamine and allowing for greater consolidation of learnt representations relative to the current study where participants engaged in a single learning session with noise. Research that provides noise with learning across multiple sessions will help to elucidate any dose dependent/practice effects. Also of note, Ripollés et al. (2016) found that subject-specific word learning success, as measured by a delayed recognition task approximately 30 min after the initial encoding session, was correlated with connection strength among the hippocampus, VS and SN/VTA. Such findings prompt the need to consider whether there may be neurological markers that predict whether noise is successful at promoting word learning and/or the duration of its effects.

Turning to the role of attention, in contrast to our hypotheses, the effect of white noise on learning was not influenced by participant executive attention capacity at either the immediate or delayed recognition test. This result is consistent with the Angwin et al. (2017) findings that executive attention had no impact on improvements to word learning induced by noise, but contrasts with other research showing that attentional capacity mediates the impact of white noise on performance of other tasks (Angwin et al., 2018; Helps et al., 2014; Soderlund et al., 2007, 2010). Given that the present study tested only university students, additional research with participants showing a more diverse range of attention capacity or with attentional difficulties (e.g., ADHD) is warranted in order to explore this issue further.

The findings also prompt other avenues for further research. Research suggests that the noise levels which maximise the benefit of subthreshold stochastic resonance for human auditory processing may fall within a narrow range (Ries, 2007). Similarly, the same may be true for suprathreshold stochastic resonance. Whilst the use of a fixed intensity of white noise is common in this field, additional research is required to identify the optimal range of noise for suprathreshold stochastic resonance and how this can be established for individual participants. Such research could include tailoring noise intensity to individual hearing thresholds. Utilizing EEG, studies have shown that white noise modulates brain activity during auditory and visual processing, and in somatosensory tasks (Gleiss & Kayser, 2014; Ohbayashi, Kakigi, & Nakata, 2017; Ward, MacLean, & Kirschner, 2010). Given the large body of ERP research on new word learning (Angwin, Phua, & Copland, 2014; Batterink & Neville, 2011; Borovsky, Elman, & Kutas, 2012; Mestres-Missé et al., 2007; Perfetti, Wlotko, & Hart, 2005), further research using ERPs may provide important insight into the nature of learning enhancement induced by white noise. The use of additional ‘implicit’ measures of learning would also add value to future research, given such measures can prove sensitive to memory biases even when stimuli are not explicitly remembered (Eden et al., 2014).

Finally, the findings have potential implications for research in people with tinnitus. Speech comprehension is impaired in people with tinnitus, particularly in the presence of additional noise, and it has been proposed that such difficulties could potentially be linked to deficits of divided or selective attention as a result of the phantom noise (Ivansic et al., 2017). Research also suggests that tinnitus may arise from stochastic resonance effects within the auditory pathway, as a means of compensating for hearing loss (Krauss et al., 2016). Accordingly, investigating word learning in people with tinnitus, with and without the provision of additional white noise, may prove worthy of exploration.

5. Conclusions

White noise facilitated the short term recognition of novel word meanings learned via sentence context, however the effect was not mediated by participant executive attention capacity. The facilitative effect of white noise on learning may be driven by modulation of dopaminergic circuitry that drives memory formation. The findings provide impetus for further research to confirm the underlying neural mechanisms, determine whether white noise can be tailored to create longer term improvements, and examine whether white noise has utility as a non-pharmacological approach to treatment for language and/or learning difficulties.

Declaration of Competing Interest

None.

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