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RESEARCH

Beta and gamma binaural beats enhance auditory sentence comprehension

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Abstract

Binaural beats—an auditory illusion produced when two pure tones of slightly different frequencies are dichotically presented—have been shown to modulate various cognitive and psychological states. Here, we investigated the effects of binaural beat stimulation on auditory sentence processing that required interpretation of syntactic relations (Experiment 1) or an evaluation of syntactic well formedness (Experiment 2) with a large cohort of healthy young adults ($N=200$). In both experiments, participants performed a language task after listening to one of four sounds (i.e., between-subject design): theta (7 Hz), beta (18 Hz), and gamma (40 Hz) binaural beats embedded in music, or the music only (baseline). In Experiment 1, 100 participants indicated the gender of a noun linked to a transitive action verb in spoken sentences containing either a subject or object-relative center-embedded clause. We found that both beta and gamma binaural beats yielded better performance, compared to the baseline, especially for syntactically more complex object-relative sentences. To determine if the binaural beat effect can be generalized to another type of syntactic analysis, we conducted Experiment 2 in which another 100 participants indicated whether or not there was a grammatical error in spoken sentences. However, none of the binaural beats yielded better performance for this task indicating that the benefit of beta and gamma binaural beats may be specific to the interpretation of syntactic relations. Together, we demonstrate, for the first time, the positive impact of binaural beats on auditory language comprehension. Both theoretical and practical implications are discussed.

Introduction

The binaural beat refers to an auditory illusion generated by the dichotic presentation of two pure tones with a slight difference in frequency. For example, if a 250 Hz pure tone is presented to the right ear while a 290 Hz pure tone is presented to the left ear, the brain will generate a de novo sound corresponding to the frequency mismatch, i.e., 40 Hz (Fig. 1A). The sound from each ear is thought to be integrated at the level of the brainstem, specifically in the inferior colliculi and the superior olivary nuclei (Oster, 1973; Wernick & Starr, 1968). Studies using electroencephalography (EEG) have shown that binaural beats give rise to neural entrainment over multiple frequency ranges including theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (> 30 Hz) bands (Ala et al., 2018; Beauchene et al., 2016; Becher et al., 2015; Draganova et al., 2008; Jirakittayakorn & Wongsawat, 2017; Perez et al., 2020; Pratt et al., 2010). For instance, a 7 Hz binaural beat stimulation increased the relative power and connectivity of the theta-band (4–8 Hz) EEG activities in the temporal and parietal lobes (Ala et al., 2018). Such neural entrainment by binaural beats is theorized to occur via brain oscillations phase-locked to external rhythms (Lakatos et al., 2019; Schroeder & Lakatos, 2009).

A growing body of studies have demonstrated that binaural beat stimulation improves cognitive performance as well as psychological states (see Chaieb et al., 2015 and Garcia-Argibay et al., 2019a for a review and a meta-analysis respectively). For instance, Beauchene et al., (2016, 2017) showed that participants performed better on a visuospatial and an N-back working memory task while listening to a beta (15 Hz) binaural beat compared to silence. They also found that cortical connectivity along the frontoparietal

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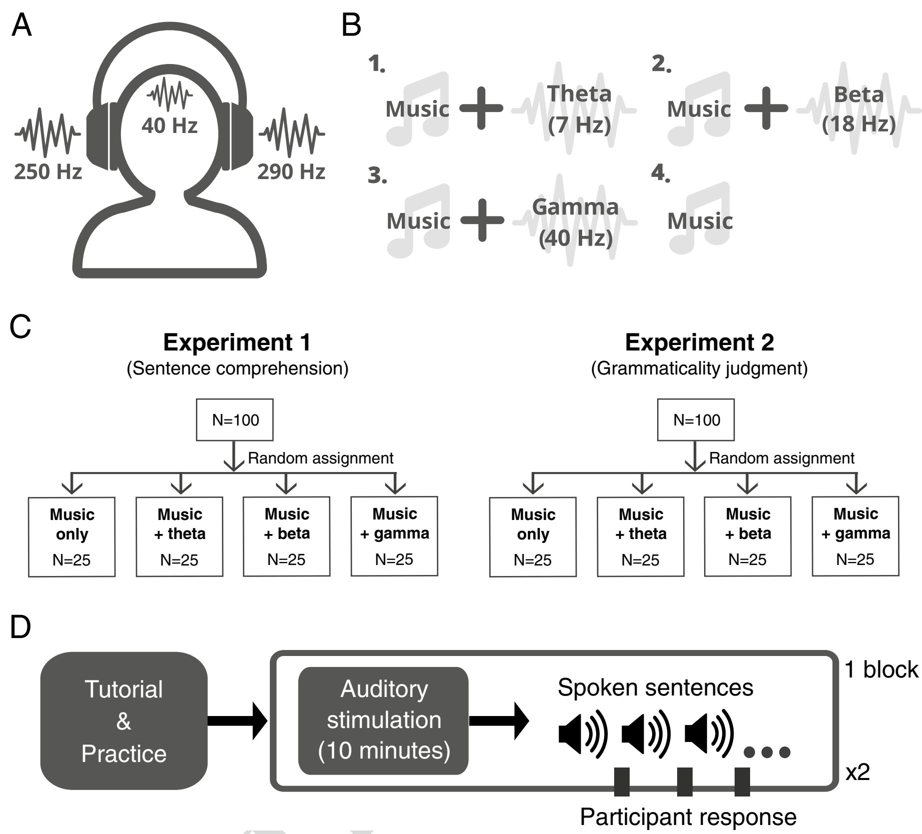

Fig. 1 **A** A visual diagram of binaural beat formation. When a 250 Hz pure tone is presented in the right ear while a 290 Hz pure tone is presented to the left ear, the brain will generate the binaural beat with a frequency of 40 Hz. **B** Four auditory conditions to which each participant is randomly assigned. **C** A diagram of the design of two experiments. **D** A schematic of the experimental procedures. Participants underwent a total of two task blocks

network increased when listening to the 15 Hz binaural beat (Beauchene et al., 2016, 2017). In addition, beta binaural beats have been shown to facilitate long-term memory (20 Hz: Garcia-Argibay et al., 2019b) and vigilance (16–24 Hz; Lane et al., 1998). Other studies have reported the positive effects of gamma binaural beats on attention (40 Hz: Colzato et al., 2017; Engelbregt et al., 2019, 2021; Reedijk et al., 2015; Ross & Lopez, 2020), theta binaural beats on verbal memory (5 Hz: Ortiz et al., 2008) and theta or alpha binaural beats on anxiety (9 Hz: Isik et al., 2017; 4-7 Hz: Mallik & Russo, 2022; 10 Hz: Wiwatwongwana et al., 2016). Nevertheless, there are some studies reporting lack of effects of binaural beats (e.g., a significant effect on accuracy but not on reaction time; Engelbregt et al., 2021). All in all, the binaural research field is still at its infancy necessitating more rigor for replication and corroboration.

In the present behavioral study, we investigated whether binaural beats facilitate auditory sentence processing, a cognitive domain that has never been explored with this non-invasive technique. We recruited 200 young adults across two language experiments (Fig. 1C), each of which entailed different syntactic operations while listening to a series of spoken sentences (see below for more detail). In both experiments, participants were presented with slow, non-rhythmic music mixed with or without binaural beats for 10 min prior to performing a language task (Fig. 1B, D). The exposure duration was chosen based on a recent study showing that 9 min of binaural beat stimulation induced connectivity changes across cortical regions (Ala et al., 2018).

Experiment 1

After the binaural beat stimulation, the participants underwent a language task involving syntactic interpretation of the noun–verb relation in a series of spoken sentences (Table 1). These sentences were adopted and modified from a previous study (Lee et al., 2020) that contained either a center-embedded subject- (e.g., ‘Kings that help queens are nice’) or object-relative clause (e.g., ‘Kings that queens help are nice’) (see Methods for more details). Object-relative sentences are more difficult than subject-relative sentences to comprehend due to the syntactically non-canonical structure (MacDonald & Christiansen, 2002; Wells et al., 2009) and higher demand on working memory (Just & Carpenter, 1992; King & Just, 1991).

We used binaural beats of the theta (7 Hz), beta (18 Hz), and gamma (40 Hz) frequency bands because each of these bands has been associated with different aspects of sentence comprehension processing in previous research. For example, beta and gamma oscillations are thought to mediate core language functions syntactic and semantic operations

Table 1 Sentence examples used in Experiment 1

Sentence type	Example	Correct answer
Subject relative	Gentlemen that **assist** ladies adore children	Male
	Gentlemen that adore ladies **assist** children	Male
Object relative	Gentlemen that ladies **assist** adore children	Female
	Gentlemen that ladies adore **assist** children	Male

The embedded clause is underlined, and the target action verb is in bold face

respectively during sentence comprehension (Prystauka & Lewis, 2019). Bastiaansen et al., (2010) demonstrated a gradual increase in beta power over the course of syntactically well-formed sentences compared to randomly organized word sequences. Also, increased gamma power has been observed in response to semantically congruent sentences, but not to sentences with semantic anomalies (Hald et al., 2006). Critically, Bastiaansen and Hagoort (2015) demonstrated a functional segregation between beta and gamma frequencies in a single study wherein beta power was increased in response to syntactically correct sentences compared to incorrect sentences while gamma power was increased in response to semantically coherent sentences compared to meaningless sentences. Theta power has been shown to increase with a greater working memory load (Jensen & Tesche, 2002; Krause et al., 2000) and during on-line sentence processing (Bastiaansen et al., 2002, 2010) likely due to its domain-general role in working memory during sentence comprehension (Bastiaansen & Hagoort, 2003).

Based on the implications of neural oscillations in the theta, beta, and gamma frequency bands during language comprehension, and especially with sentences containing object- vs. subject-relative clauses (Weiss et al., 2005), we hypothesized that binaural beats in any, if not all, of these frequency bands would enhance sentence comprehension performance. In particular, we expected to observe a more pronounced impact of these binaural beats in the more difficult object-relative, compared to subject-relative, sentences.

Methods

Participants

One hundred undergraduate students from the University of Texas at Dallas (63 females, 36 males, and 1 other/not specified, 18–37 years, mean age = 21.6 years, SD = 3.5 years) participated in Experiment 1 for course credits or monetary compensation ($15 gift card). All of the participants were native speakers of American English, had normal vision and hearing, and had no known history of cognitive, developmental, or neurological disorders. They consented to participating in the study, which was approved by the University of Texas at Dallas Institutional Review Board (IRB-21-109).

Stimuli and procedures

All sound stimuli were presented at a preset volume (70 dB SPL) via Sennheiser HD-280 headphones. For the binaural beat stimulation, a 250 Hz pure tone was presented to the right ear as a carrier frequency while another pure tone with 257 Hz, 268 Hz, or 290 Hz was presented to the left ear, eliciting theta (7 Hz), beta (18 Hz), and gamma (40 Hz) binaural beats, respectively (Fig. 1B). The two pure tones were mixed with an excerpt of slow-tempo, non-rhythmical music (Dangol, 2019) at a signal-to-music ratio of –2 dB (Online Resource 1) to help participants endure prolonged exposure to binaural beats. In the baseline condition, the same music was played without binaural beats. Auditory sentence stimuli were generated using the Google Text-to-Speech and the speaker voice was set to an American-English speaking male (Online Resource 2). Experiments were conducted using Matlab R2021 (Mathworks, MA) in a dimly lit sound-proof booth.

For the sentence comprehension task, the stimuli were comprised of 128 spoken sentences, each of which consisted of six words: a male noun (e.g., boys, uncles, kings), a female noun (e.g., girls, aunts, queens), a gender-neutral noun (e.g., children, students, doctors), a relative pronoun 'that', a transitive action verb (e.g., help, hug, bully), and one of four transitive preference verbs: love, adore, hate, and dislike. Each sentence contained either a subject or object-relative center-embedded clause, which was solely determined by switching the temporal order of the same noun and verb in the relative clause within the sentence (Table 1). For each sentence trial, participants indicated the gender of the individuals performing an action, while disregarding those who love/adore/hate/dislike others, by pressing either the 'male' (left arrow) or 'female' (right arrow) key within 5 s. The sentence type (i.e., subject or object-relative) and the gender of the agent (i.e., female or male) were counterbalanced across trials.

Participants were randomly assigned to one of four conditions (Fig. 1C): music + theta (7 Hz), music + beta (18 Hz), music + gamma (40 Hz), or music only ($N = 25$ for each

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condition). Participants were first familiarized with the language task by undergoing 16 practice trials, during which they received feedback immediately after each response. Sentences used for the practice session were not presented during the main experiment. After the practice was completed, participants listened to each of these 4 sounds for 10 min while fixating their eyes onto a speaker icon on the screen. Participants were not explicitly informed about the presence of a binaural beat embedded in the music. Immediately after listening to the sound, participants underwent 64 trials of the sentence comprehension task (block1). A 15 s break was provided every 16 trials. This procedure was repeated with another 64 trials (block2). No feedback was provided during the two task blocks. Together, the duration of the experiment ranged from 50 to 60 min in total, including the tutorial/practice (10 min), binaural beat stimulation ($2 \times 10 = 20$ min), and the main task (2×10–15 min per block = 20–30 min) (Fig. 1D).

Data analysis

We opted to use a logistic regression model to analyze the binomial accuracy data. The trial-by-trial accuracy data were entered into a mixed effects logistic regression model using the glmer function of the *lme4* package (Bates et al., 2015) in R 4.2.1. The model included the factors of sentence type (i.e., subject- and object-relative), binaural beat condition (i.e., theta, beta, gamma, and music only), and an interaction between the two factors as fixed effects. In addition, the participant factor was included as a random intercept. The no-response trials or those with late (> 5 s)-responses were coded as incorrect (0.35% of the entire trials across participants). The statistical significance of the fixed effects was assessed using the Type III Wald chi-square tests of the *car* package (Fox et al., 2012). Upon a significant interaction effect (see below), we examined differences in accuracy within object-relative sentences between the music-only group and each of the three binaural beat groups using a one-sided general linear hypothesis test (glht) of the *multcomp* package (Hothorn et al., 2016). The multiple comparisons were corrected using the Dunnett's single-step method (Dunnett, 1955). Reaction time was not analyzed given large individual differences in accuracy.

Results

As expected, there was a significant main effect of sentence type on accuracy [$\chi^2(1) = 322.17$, $p < 0.001$], with a lower score in object-relative ($M = 77.1\%$) compared to subject-relative sentences ($M = 93.9\%$). We also found a marginally significant main effect of binaural beat condition [$\chi^2(3) = 7.32$, $p = 0.062$], with relatively higher mean accuracies in the theta ($M = 83.7\%$), beta, ($M = 88.2\%$), and gamma ($M = 89.1\%$) binaural beat conditions than in the baseline (i.e., music-only) condition ($M = 81.0\%$). Critically, we found a significant interaction [$\chi^2(3) = 20.68$, $p < 0.001$] due to a more robust binaural beat effect on the object-relative sentences compared to subject-relative sentences (Fig. 2).

To further examine the significant interaction effect, we compared performance between the baseline group and each of the binaural beat groups within object-relative sentences. The results showed higher accuracy in the beta (81.8%) [$z = 2.21$, $p = 0.035$] and gamma ($M = 83.1\%$) [$z = 2.29$, $p = 0.029$] than in the baseline ($M = 68.5\%$). However, the slight increase in theta ($M = 74.8\%$) relative to baseline did not reach statistical significance [$z = 0.95$, $p = 0.346$].

Experiment 2

The findings in Experiment 1 naturally invite the following questions: could the binaural beat effect be generalized to different kinds of syntactic operations during auditory sentence comprehension? That is, would either beta or gamma binaural beats turn out to be significant when another syntactic task is used? To address this, we constructed another set of object-relative and subject-relative sentences, half of which contained a morpho-syntactic error on subject-verb agreement or verb tense (Table 2). For this type of syntactic analysis, both the theta and beta frequency bands have been implicated in previous research, in which the presence of a syntactic violation elicited increased oscillatory power in the theta band and decreased power in the beta band (Kielar et al., 2015; Lewis et al., 2016; Pérez et al., 2012). While the increase of theta power is thought to reflect a greater working memory demand in processing sentences

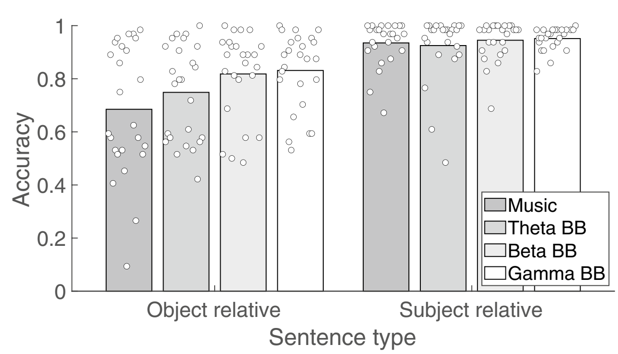

Fig. 2 The accuracy of the sentence comprehension task on object and subject-relative sentences in the three binaural beat conditions and the music-only condition. Circles indicate individual data points. Participants in the beta and gamma binaural beat condition, but not theta, exhibited significantly better performance for object-relative sentences than those in the baseline music-only condition

Table 2 Examples used in the grammaticality judgment task (Experiment 2)

Sentence type	Example	Type of error
Subject relative	The customer that tips (*tip*) the waitress saddles horses every day	SVA (relative)
	Every year, the criminals that avoid the police go (*goes*) to the jail	SVA (main)
	Yesterday, the father that keeps the boys wanted (*wants*) toothpaste	Tense
Object relative	The student that the nephew trusts (*trust*) fixed the mistake yesterday	SVA (relative)
	Every week, the ladies that the baby loves watch (*watches*) the movie	SVA (main)
	The animal that the children dislike hunted (*hunts*) a prey last month	Tense

The embedded clause is underlined, and the morpho-syntactic violation is shown as italic in the parenthesis. *SVA* subject-verb agreement

with syntactic violations (Prystauka & Lewis, 2019), the decrease of beta power has been interpreted as reflecting a disruption of building up syntactic structures. In addition, decreased gamma power has been associated with the presence of a semantic anomaly within syntactically well-formed sentences (e.g., ‘The hose can *bake* water on the flowers’) (Penolazzi et al., 2009; Rommers et al., 2013; Wang et al., 2012). Thus, we considered the following scenarios: (1) Based on the previous literature, theta and/or beta binaural beats would enhance grammaticality judgment performance. (2) Because of the minimal influence of morpho-syntactic errors (e.g., go vs. goes) on the overall meaning of the sentence, we expected that a gamma binaural beat may yield little-to-no effects.

Method

Participants

Another one hundred undergraduate students from the University of Texas at Dallas (67 females and 33 males, 18–27 years, mean age = 19.9 years, SD = 1.8 years) participated in Experiment 2 for course credits or monetary compensation ($15 gift card). None of the participants had participated in Experiment 1. All the participants were native speakers of American English, had normal vision and hearing, and had no known history of cognitive, developmental, or neurological disorders. They consented to participating in the study, which was approved by the University of Texas at Dallas Institutional Review Board (IRB-21-109).

Stimuli and procedures

The binaural beat stimuli and procedures were identical to those used in Experiment 1, except for the language material and task. In Experiment 2, the language stimuli were comprised of 96 sentences, each of which contained either a subject- or object-relative clause and a time adverb phrase (e.g., every week, last year) (Table 2). Half of the sentences were grammatical while the other half were ungrammatical, containing a morpho-syntactic error. There were three types of violations: a subject-verb agreement error within the relative phrase, a subject-verb agreement error in the main phrase, and a past tense error (Table 2). The sentence and error types were counterbalanced across trials. For each trial, participants were instructed to indicate whether or not a given sentence was grammatically correct by pressing either the ‘correct’ (right arrow) or incorrect’ (left arrow) key. There was no time constraint in this task to ensure obtainment of *d’* scores from every trial. Reaction time was not analyzed given large individual differences in accuracy.

Participants were randomly assigned to one of three binaural beat conditions and a baseline condition: music + theta (7 Hz), music + beta (18 Hz), music + gamma (40 Hz), or music only ($N = 25$ for each condition) (Fig. 1B, C). Participants received 8 practice trials, during which they were given feedback immediately after each response. The sentence materials used for the practice were not included in the main experiment. After listening to the music, the participants underwent 48 trials of the grammaticality judgment task (block1). Participants took a 15 s break after every 12 trials. The task duration, including breaks, ranged from 10 to 15 min. This procedure was repeated with another round of the grammaticality judgment task consisting of 48 trials (block2). No feedback was provided during the actual task (Fig. 1D). The experiment took approximately 45 to 55 min before completion, including the practice (5 min), binaural beat stimulation ($2 \times 10 = 20$ min), and the main task (2×10–15 min per block = 20–30 min) (Fig. 1D).

Data analysis

We computed a d-prime (*d’*) score for each sentence type. A *d′* score was calculated by subtracting the z-scores of false alarm rate from the z-scores of hit rate. To prevent an indefinite *d’* score, hits and false alarms of 0 and 1 were replaced with 1/24 and 23/24 respectively (Macmillan & Kaplan, 1985). The resulting data were submitted to a linear mixed effects model analysis using the lmer function of the *lme4* package with fixed effects of sentence type and binaural beat condition, as well as a random intercept of participant.

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Results

Consistent with the Experiment 1, there was a significant main effect of sentence type on *d'* [$F(1,99)=31.36$, $p<0.001$], with lower accuracy in object-relative ($M=1.19$) compared to subject-relative ($M=1.51$) sentences (Fig. 3). Although the group mean accuracy was slightly higher in the three binaural beat groups than in the baseline group, there was neither a main effect of binaural beat condition [$F(1,99)=1.37$, $p=0.255$] nor a significant interaction [$F(3,99)=0.21$, $p=0.892$]. Thus, the binaural beat effects observed in experiment 1 did not translate to the grammaticality evaluation task used in experiment 2.

Discussion

In the present study with a large cohort of young adults ($N=200$), we examined the impact of binaural beats on auditory sentence processing, a hitherto unexplored research question. In Experiment 1, participants were presented with sentences containing either a subject or object-relative clause, which required a rapid interpretation of syntactic relations between noun and verb phrases in a given sentence. As expected, object-relative sentences yielded lower accuracy in comparison to subject-relative sentences due to their non-canonicity (Wells et al., 2009) and/or higher working memory load (King & Just, 1991). Importantly, we found that the beta and gamma binaural beats significantly enhanced the task performance for the object-relative sentences relative to the baseline. Experiment 2 was subsequently designed to see if the binaural beat effect could be generalized to another linguistic operation (i.e., grammaticality judgment), which yielded non-significant results. This suggests that the effects of binaural beats on auditory sentence processing are rather specific. In what follows, we discuss the theoretical and practical implications of the current findings.

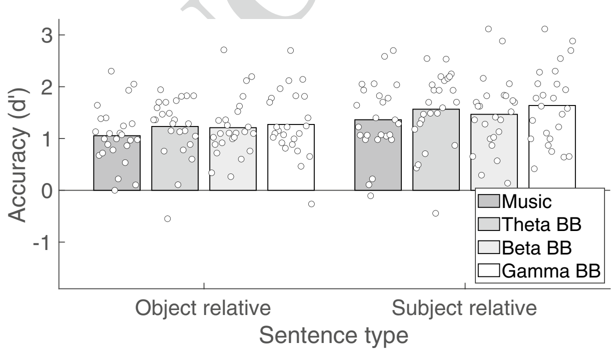

Fig. 3 The accuracy of the grammaticality judgment task in the three binaural beat conditions and the music-only baseline condition. Circles indicate individual data points. Performance was comparable across all the conditions

The functional role of beta binaural beat stimulation on auditory sentence processing

Beta binaural beat stimulation significantly enhanced auditory sentence comprehension involving the syntactic interpretation of the relationship between an action verb and noun in a sentence, especially in the non-canonical object-relative sentences in Experiment 1. Indeed, beta band oscillations have been implicated in on-line sentence processing that involves various syntactic operations. For example, increased beta power has been observed while reading syntactically well-formed sentences (Bastiaansen & Hagoort, 2015). Also, object-relative sentences have been shown to elicit greater beta coherence compared to subject-relative sentences (Weiss et al., 2005), which may reflect a considerable processing burden towards analyzing the non-canonical syntactic structure of object-relative sentences. Our findings suggest that the beta binaural beat may have increased the beta power and/or coherence during sentence processing, which could help with the difficulty of analyzing object-relative sentences—an important follow-up question raised by the current behavioral finding.

It is also conceivable that the beta binaural beat might have enhanced verbal working memory (Beauchene et al., 2017). Note that there are two grammatical agents that must be maintained in working memory for objective-relative sentences, whereas only a single agent is present in subject-relative sentences (King & Just, 1991; see Table 1). Relatedly, increased beta power has been elicited by listening to sentences with a long compared to a short subject-verb distance, indicating a consequence of working memory demand on beta frequency oscillations during sentence processing (Meyer et al., 2013). This explanation is consistent with a recent theoretical account that the increase in beta oscillations during sentence processing reflects an active maintenance of the ongoing sentence-level representations (Lewis et al., 2015; Weiss & Mueller, 2012). However, the working memory account may not be fully compatible with the findings in Experiment 1, given the lack of the beta binaural beat effect in Experiment 2, which also required listeners to maintain linguistic elements in a sentence (McDonald, 2000; Noonan et al., 2014). Although future studies are warranted, the beta binaural beat may have enhanced syntactic interpretation, rather than the domain-general working memory.

The functional role of gamma binaural beat stimulation on auditory sentence processing

We also found that the gamma binaural beat yielded performance enhancement during sentence comprehension

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in Experiment 1. Gamma band oscillations have been frequently associated with semantic components of sentence-level language processing, evidenced by decreased gamma power in response to semantically anomalous words (Penolazzi et al., 2009; Rommers et al., 2013; Wang et al., 2012). Similarly, Bastiaansen and Hagoort (2015) reported that semantically congruent sentences elicited increased gamma power compared to semantically uninterpretable sentences or word lists, leading them to conclude that gamma-band activities support semantic unification. In Experiment 1, although the agent linked to an action verb in a given sentence was determined solely by its syntactic structure (i.e., subject or object-relative), the task would inevitably require lexical-semantic processing of the nouns and verbs. Furthermore, each sentence might differ in the degree of semantic plausibility, which could have affected the interpretation of object-relative sentences (e.g., Gennari & MacDonald, 2008). As such, these semantic analyses may have benefited from gamma binaural beat stimulation. It is also plausible that the gamma binaural beat, along with beta, may have led to improved syntactic processing given both semantic and syntactic operations are often intertwined and influence each other (e.g., Gámez & Vasilyeva, 2015; Gunter et al., 2000). Unfortunately, the current sentence stimuli cannot allow us to dissociate the functional role of gamma frequency on semantic from syntactic processes, which necessitates a follow-up study.

Another possibility is that the gamma binaural beat may have provided an attentional boost (Fell et al., 2003; Fries, 2015; Lakatos et al., 2008). Indeed, gamma binaural beats have been used to improve performance on various attention tasks, including a visual feature binding task (Colzato et al., 2017), an attentional blink task (Reedijk et al., 2015; Ross & Lopez, 2020), the Flanker task (Engelbregt et al., 2021), and a visual task in a dual-task paradigm (Hommel et al., 2016). For example, Engelbregt et al., (2021) exposed participants to a gamma binaural beat or pink noise while performing the Flanker task, which gauged their ability to selectively attend to a target stimulus in the presence of distractors. They found that the gamma binaural beat significantly reduced the number of incorrect responses compared to pink noise, indicating an enhancement of selective attention. Nevertheless, the lack of efficacy of the gamma binaural beat in Experiment 2 may weaken this interpretation.

The selective impact of beta and gamma binaural beats on auditory sentence processing

Our findings suggest that the beta and gamma binaural beats have functional specificity since they only enhanced syntactic interpretation of the noun–verb relation in Experiment 1, not morpho-syntactic error detection in Experiment2. Indeed, we have recently reported dissociable neuroanatomical systems devoted to different subsets of syntactic processing (Heard & Lee, 2020). Such dissociation within the language system was previously reported in clinical research as well. For example, aphasic patients preserved the ability to detect grammatical errors in sentences despite severe comprehension deficits (Linebarger et al., 1983; Wulfeck, 1988). Conversely, patients with cerebellar lesions were less impaired in sentence comprehension, compared to their grammaticality judgment ability (Justus, 2004). The present results are in line with the view that constructing a syntactic representation for grammaticality judgment is dissociable from the analysis of syntactic relations between words for sentence comprehension (Linebarger et al., 1983).

The functional role of theta binaural beat stimulation on auditory sentence processing

Although the theta binaural beat yielded numerically higher accuracy than the music-only baseline condition, the difference did not reach statistical significance in both experiments. Theta oscillations are related to working memory functions, e.g., increased theta power is often associated with a greater working memory load (Hsieh & Ranganath, 2014; Jensen & Tesche, 2002; Scheeringa et al., 2009). Indeed, the theta binaural beat has been used to enhance participants' immediate recall of verbal items (Ortiz et al., 2008), leading us to hypothesize that the theta binaural beat would improve auditory sentence processing by facilitating the domain-general processing. However, theta was not as effective as beta or gamma in auditory sentence comprehension, negating the working memory hypothesis. Similar to our data, a past study showed that the theta binaural beat failed to improve performance on an N-back working memory task (Beauchene et al., 2017). Note, however, that this study used 5 min of theta binaural beat stimulation. As mentioned earlier, we chose 10 min of binaural beat stimulation based upon the evidence that a 9-min duration was sufficient to induce neural entrainment (Ala et al., 2018; Jirakittayakorn & Wongsawat, 2017). While our study failed to show a theta binaural beat effect, Ortiz et al. (2008) found a significant improvement in verbal memory using 15 min of theta binaural beat stimulation. A future study should consider employing various lengths of theta binaural beat stimulation to systemically determine the duration effect.

Other considerations

In the current study, we used binaural beats embedded in a slow, non-rhythmic music unbeknown to participants. Similarly, a recent study showed that theta binaural beat stimulation combined with personalized music reduced anxiety (Mallik & Russo, 2022). Importantly, however, they did not find the binaural beat effect without music, suggesting an interaction between binaural beats and music. From one point of view, these findings suggest that binaural beats can be practically used along with music as a non-invasive sound therapy. However, the interaction effect must be explained by follow-up experiments that include a binaural beat only condition.

Another important investigation is to determine how long the after-effects of binaural beat stimulation would last. The current study was not designed to examine the sustainability of the binaural beat effects. From a therapeutic perspective, this is a critical and timely question. It would be informative in future studies to establish the duration of binaural beat effects, as is the case with the application of neurostimulation (Kasten et al., 2016; Neuling et al., 2013; Reinhart & Nguyen, 2019; Wischnewski et al., 2019).

Conclusion

In sum, we presented novel evidence that beta and gamma binaural beats positively impact an auditory language comprehension task involving the syntactic analysis between a noun and a verb at the sentence level. Notably, these binaural beats may have helped overcome the difficulty of comprehending sentences with a non-canonical syntactic structure (i.e., object-relative). Nevertheless, such binaural beat effects were not generalized to another language task involving morpho-syntactic error detection. Future research is needed to elucidate the role of beta and gamma binaural beats on complex sentence comprehension that entails both core linguistic operations (e.g., syntax and semantics) and domain-general processing (e.g., working memory). Together, our behavioral study establishes the first step towards understanding the impact of binaural beats on auditory sentence processing, which can potentially serve as a novel therapeutic means for treating language disorders.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00426-023-01808-w.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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References

Ala, T. S., Ahmadi-Pajouh, M. A., & Nasrabadi, A. M. (2018). Cumulative effects of theta binaural beats on brain power and functional connectivity. *Biomedical Signal Processing and Control, 42*, 242–252. https://doi.org/10.1016/j.bspc.2018.01.022

Bastiaansen, M., & Hagoort, P. (2003). Event-induced theta responses as a window on the dynamics of memory. *Cortex, 39*(4–5), 967–992. https://doi.org/10.1016/S00109452(08)70876

Bastiaansen, M., & Hagoort, P. (2015). Frequency-based segregation of syntactic and semantic unification during online sentence level language comprehension. *Journal of Cognitive Neuroscience, 27*(11), 2095–2107. https://doi.org/10.1162/jocn_a_00829

Bastiaansen, M., van Berkum, J. J., & Hagoort, P. (2002). Event-related theta power increases in the human EEG during online sentence processing. *Neuroscience Letters, 323*(1), 13–16. https://doi.org/10.1016/s0304-3940(01)02535-6

Bastiaansen, M., Magyari, L., & Hagoort, P. (2010). Syntactic unification operations are reflected in oscillatory dynamics during on-line sentence comprehension. *Journal of Cognitive Neuroscience, 22*(7), 1333–1347. https://doi.org/10.1162/jocn.2009.21283

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*. https://doi.org/10.18637/jss.v067.i01

Beauchene, C., Abaid, N., Moran, R., Diana, R. A., & Leonessa, A. (2016). The effect of binaural beats on visuospatial working memory and cortical connectivity. *PLoS ONE, 11*(11), 0166630.

Beauchene, C., Abaid, N., Moran, R., Diana, R. A., & Leonessa, A. (2017). The effect of binaural beats on verbal working memory and cortical connectivity. *Journal of Neural Engineering, 14*(2), 026014.

Becher, A. K., Höhne, M., Axmacher, N., Chaieb, L., Elger, C. E., & Fell, J. (2015). Intracranial electroencephalography power and phase synchronization changes during monaural and binaural beat stimulation. *European Journal of Neuroscience, 41*(2), 254–263. https://doi.org/10.1111/ejn.12760

Chaieb, L., Wilpert, E. C., Reber, T. P., & Fell, J. (2015). Auditory beat stimulation and its effects on cognition and mood states. *Frontiers in Psychiatry, 6*, 70. https://doi.org/10.3389/fpsyt.2015.00070

Colzato, L. S., Barone, H., Sellaro, R., & Hommel, B. (2017). More attentional focusing through binaural beats: Evidence from the global–local task. *Psychological Research Psychologische Forschung, 81*(1), 271–277. https://doi.org/10.1007/s00426-015-0727-0

Dangol, P. (2019). Remove mental blockages & subconscious negativity [Song]. *On Inner Guidance*.

Draganova, R., Ross, B., Wollbrink, A., & Pantev, C. (2008). Cortical steady-state responses to central and peripheral auditory beats. *Cerebral Cortex, 18*(5), 1193–1200. https://doi.org/10.1093/cercor/bhm153

Dunnett, C. W. (1955). A multiple comparison procedure for comparing several treatments with a control. *Journal of the American Statistical Association, 50*(272), 1096–1121. https://doi.org/10.1080/01621459.1955.10501294

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Engelbregt, H., Meijburg, N., Schulten, M., Pogarell, O., & Deijen, J. B. (2019). The effects of binaural and monoaural beat stimulation on cognitive functioning in subjects with different levels of emotionality. *Advances in Cognitive Psychology, 15*(3), 199. https://doi.org/10.5709/acp-0268-8

Engelbregt, H., Barmentlo, M., Keeser, D., Pogarell, O., & Deijen, J. B. (2021). Effects of binaural and monaural beat stimulation on attention and EEG. *Experimental Brain Research, 239*(9), 2781–2791. https://doi.org/10.1007/s00221-021-06155-z

Fell, J., Fernández, G., Klaver, P., Elger, C. E., & Fries, P. (2003). Is synchronized neuronal gamma activity relevant for selective attention? *Brain Research Reviews, 42*(3), 265–272. https://doi.org/10.1016/S0165-0173(03)00178-4

Fox, J., Weisberg, S., Adler, D., Bates, D., Baud-Bovy, G., Ellison, S., ... & Monette, G. (2012). Package 'car'. *Vienna: R Foundation for Statistical Computing, 16*

Fries, P. (2015). Rhythms for cognition: Communication through coherence. *Neuron, 88*(1), 220–235. https://doi.org/10.1016/j.neuron.2015.09.034

Gámez, P. B., & Vasilyeva, M. (2015). Exploring interactions between semantic and syntactic processes: The role of animacy in syntactic priming. *Journal of Experimental Child Psychology, 138*, 15–30. https://doi.org/10.1016/j.jecp.2015.04.009

Garcia-Argibay, M., Santed, M. A., & Reales, J. M. (2019a). Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: A meta-analysis. *Psychological Research Psychologische Forschung, 83*(2), 357–372. https://doi.org/10.1007/s00426-018-1066-8

Garcia-Argibay, M., Santed, M. A., & Reales, J. M. (2019b). Binaural auditory beats affect long-term memory. *Psychological Research Psychologische Forschung, 83*(6), 1124–1136. https://doi.org/10.1007/s00426-017-0959-2

Gennari, S. P., & MacDonald, M. C. (2008). Semantic indeterminacy in object relative clauses. *Journal of Memory and Language, 58*(2), 161–187. https://doi.org/10.1016/j.jml.2007.07.004

Gunter, T. C., Friederici, A. D., & Schriefers, H. (2000). Syntactic gender and semantic expectancy: ERPs reveal early autonomy and late interaction. *Journal of Cognitive Neuroscience, 12*(4), 556–568. https://doi.org/10.1162/089892900562336

Hald, L. A., Bastiaansen, M. C., & Hagoort, P. (2006). EEG theta and gamma responses to semantic violations in online sentence processing. *Brain and Language, 96*(1), 90–105. https://doi.org/10.1016/j.bandl.2005.06.007

Heard, M., & Lee, Y. S. (2020). Shared neural resources of rhythm and syntax: An ALE meta-analysis. *Neuropsychologia, 137*, 107284.

Hommel, B., Sellaro, R., Fischer, R., Borg, S., & Colzato, L. S. (2016). High-frequency binaural beats increase cognitive flexibility: Evidence from dual-task crosstalk. *Frontiers in Psychology*. https://doi.org/10.3389/fpsyg.2016.01287

Hothorn, T., Bretz, F., Westfall, P., Heiberger, R. M., Schuetzenmeister, A., Scheibe, S., & Hothorn, M. T. (2016). Package 'multcomp.' *Simultaneous Inference in General Parametric Models., 66*, 5565.

Hsieh, L.-T., & Ranganath, C. (2014). Frontal midline theta oscillations during working memory maintenance and episodic encoding and retrieval. *NeuroImage, 85*, 721–729. https://doi.org/10.1016/j.neuroimage.2013.08.003

Isik, B. K., Esen, A., Büyükerkmen, B., Kilinç, A., & Menziletoglu, D. (2017). Effectiveness of binaural beats in reducing preoperative dental anxiety. *British Journal of Oral and Maxillofacial Surgery, 55*(6), 571–574. https://doi.org/10.1016/j.bjoms.2017.02.014

Jensen, O., & Tesche, C. D. (2002). Frontal theta activity in humans increases with memory load in a working memory task: Frontal theta increases with memory load. *European Journal of Neuroscience, 15*(8), 1395–1399. https://doi.org/10.1046/j.1460-9568.2002.01975.x

Jirakittayakorn, N., & Wongsawat, Y. (2017). Brain responses to a 6-Hz binaural beat: Effects on general theta rhythm and frontal midline theta activity. *Frontiers in Neuroscience, 11*, 365. https://doi.org/10.3389/fnins.2017.00365

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*(1), 122–149. https://doi.org/10.1037/0033-295X.99.1.122

Justus, T. (2004). The cerebellum and English grammatical morphology: Evidence from production, comprehension, and grammaticality judgments. *Journal of Cognitive Neuroscience, 16*(7), 1115–1130. https://doi.org/10.1162/0898929041920513

Kasten, F. H., Dowsett, J., & Herrmann, C. S. (2016). Sustained aftereffect of α-tACS lasts up to 70 min after stimulation. *Frontiers in Human Neuroscience, 10*, 245. https://doi.org/10.3389/fnhum.2016.00245

Kielar, A., Panamsky, L., Links, K. A., & Meltzer, J. A. (2015). Localization of electrophysiological responses to semantic and syntactic anomalies in language comprehension with MEG. *NeuroImage, 105*, 507–524. https://doi.org/10.1016/j.neuroimage.2014.11.016

King, J., & Just, M. A. (1991). Individual differences in syntactic processing: The role of working memory. *Journal of Memory and Language, 30*(5), 580–602. https://doi.org/10.1016/0749-596X(91)90027-H

Krause, C. M., Sillanmäki, L., Koivisto, M., Saarela, C., Häggqvist, A., Laine, M., & Hämäläinen, H. (2000). The effects of memory load on event-related EEG desynchronization and synchronization. *Clinical Neurophysiology, 111*(11), 2071–2078. https://doi.org/10.1016/S1388-2457(00)00429-6

Lakatos, P., Karmos, G., Mehta, A. D., Ulbert, I., & Schroeder, C. E. (2008). Entrainment of neuronal oscillations as a mechanism of attentional selection. *Science, 320*(5872), 110–113. https://doi.org/10.1126/science.1154735

Lakatos, P., Gross, J., & Thut, G. (2019). A new unifying account of the roles of neuronal entrainment. *Current Biology, 29*(18), R890–R905. https://doi.org/10.1016/j.cub.2019.07.075

Lane, J. D., Kasian, S. J., Owens, J. E., & Marsh, G. R. (1998). Binaural auditory beats affect vigilance performance and mood. *Physiology & Behavior, 63*(2), 249–252. https://doi.org/10.1016/S0031-9384(97)00436-8

Lee, Y. S., Ahn, S., Holt, R. F., & Schellenberg, E. G. (2020). Rhythm and syntax processing in school-age children. *Developmental Psychology*. https://doi.org/10.1037/dev0000969

Lewis, A. G., Wang, L., & Bastiaansen, M. (2015). Fast oscillatory dynamics during language comprehension: Unification versus maintenance and prediction? *Brain and Language, 148*, 51–63. https://doi.org/10.1016/j.bandl.2015.01.003

Lewis, A. G., Lemhöfer, K., Schoffelen, J.-M., & Schriefers, H. (2016). Gender agreement violations modulate beta oscillatory dynamics during sentence comprehension: A comparison of second language learners and native speakers. *Neuropsychologia, 89*, 254–272. https://doi.org/10.1016/j.neuropsychologia.2016.06.031

Linebarger, M. C., Schwartz, M. F., & Saffran, E. M. (1983). Sensitivity to grammatical structure in so-called agrammatic aphasics. *Cognition, 13*(3), 361–392. https://doi.org/10.1016/0010-0277(83)90015-X

MacDonald, M. C., & Christiansen, M. H. (2002). Reassessing working memory: Comment on Just and Carpenter (1992) and Waters and Caplan (1996). *Psychological Review, 109*(1), 35–54. https://doi.org/10.1037/0033-295X.109.1.35

Macmillan, N. A., & Kaplan, H. L. (1985). Detection theory analysis of group data: Estimating sensitivity from average hit and false-alarm rates. *Psychological Bulletin, 98*(1), 185–199. https://doi.org/10.1037/0033-2909.98.1.185

Mallik, A., & Russo, F. A. (2022). The effects of music & auditory beat stimulation on anxiety: A randomized clinical trial. *PLoS ONE, 17*(3), 0259312.

McDonald, J. L. (2000). Grammaticality judgments in a second language: Influences of age of acquisition and native language. *Applied Psycholinguistics, 21*(3), 395–423. https://doi.org/10.1017/S0142716400003064

Meyer, L., Obleser, J., & Friederici, A. D. (2013). Left parietal alpha enhancement during working memory-intensive sentence processing. *Cortex, 49*(3), 711–721. https://doi.org/10.1016/j.cortex.2012.03.006

Neuling, T., Rach, S., & Herrmann, C. S. (2013). Orchestrating neuronal networks: Sustained after-effects of transcranial alternating current stimulation depend upon brain states. *Frontiers in Human Neuroscience, 7*, 161. https://doi.org/10.3389/fnhum.2013.00161

Noonan, N. B., Redmond, S. M., & Archibald, L. M. D. (2014). Contributions of children's linguistic and working memory proficiencies to their judgments of grammaticality. *Journal of Speech, Language, and Hearing Research, 57*(3), 979–989. https://doi.org/10.1044/2014_JSLHR-L-12-0225

Ortiz, T., Martínez, A. M., Fernández, A., Maestu, F., Campo, P., Hornero, R., Escudero, J., & Poch, J. (2008). Impact of auditory stimulation at a frequency of 5 Hz in verbal memory. *Actas Espanolas De Psiquiatria, 36*(6), 307–313.

Oster, G. (1973). Auditory beats in the brain. *Scientific American, 229*(4), 94–102. https://doi.org/10.1038/scientificamerican1073-94

Penolazzi, B., Angrilli, A., & Job, R. (2009). Gamma EEG activity induced by semantic violation during sentence reading. *Neuroscience Letters, 465*(1), 74–78. https://doi.org/10.1016/j.neulet.2009.08.065

Pérez, A., Molinaro, N., Mancini, S., Barraza, P., & Carreiras, M. (2012). Oscillatory dynamics related to the unagreement pattern in Spanish. *Neuropsychologia, 50*(11), 2584–2597. https://doi.org/10.1016/j.neuropsychologia.2012.07.009

Perez, H. D. O., Dumas, G., & Lehmann, A. (2020). Binaural beats through the auditory pathway: From brainstem to connectivity patterns. *Eneuro, 7*(2), 0232–0319.

Pratt, H., Starr, A., Michalewski, H. J., Dimitrijevic, A., Bleich, N., & Mittelman, N. (2010). A comparison of auditory evoked potentials to acoustic beats and to binaural beats. *Hearing Research, 262*(1–2), 34–44. https://doi.org/10.1016/j.heares.2010.01.013

Prystauka, Y., & Lewis, A. G. (2019). The *power* of neural oscillations to inform sentence comprehension: A linguistic perspective. *Language and Linguistics Compass*. https://doi.org/10.1111/lnc3.12347

Reedijk, S. A., Bolders, A., Colzato, L. S., & Hommel, B. (2015). Eliminating the attentional blink through binaural beats: A case for tailored cognitive enhancement. *Frontiers in Psychiatry*. https://doi.org/10.3389/fpsyt.2015.00082

Reinhart, R. M., & Nguyen, J. A. (2019). Working memory revived in older adults by synchronizing rhythmic brain circuits. *Nature Neuroscience, 22*(5), 820–827. https://doi.org/10.1038/s41593-019-0371-x

Rommers, J., Dijkstra, T., & Bastiaansen, M. (2013). Context-dependent semantic processing in the human brain: Evidence from idiom comprehension. *Journal of Cognitive Neuroscience, 25*(5), 762–776. https://doi.org/10.1162/jocn_a_00337

Ross, B., & Lopez, M. D. (2020). 40-Hz Binaural beats enhance training to mitigate the attentional blink. *Scientific Reports, 10*(1), 7002. https://doi.org/10.1038/s41598-020-63980-y

Scheeringa, R., Petersson, K. M., Oostenveld, R., Norris, D. G., Hagoort, P., & Bastiaansen, M. (2009). Trial-by-trial coupling between EEG and BOLD identifies networks related to alpha and theta EEG power increases during working memory maintenance. *NeuroImage, 44*(3), 1224–1238. https://doi.org/10.1016/j.neuroimage.2008.08.041

Schroeder, C. E., & Lakatos, P. (2009). Low-frequency neuronal oscillations as instruments of sensory selection. *Trends in Neurosciences, 32*(1), 9–18. https://doi.org/10.1016/j.tins.2008.09.012

Wang, L., Zhu, Z., & Bastiaansen, M. (2012). Integration or predictability? A further specification of the functional role of gamma oscillations in language comprehension. *Frontiers in Psychology., 11*, 435. https://doi.org/10.3389/fpsyg.2012.00187

Weiss, S., & Mueller, H. M. (2012). "Too many betas do not spoil the broth": The role of beta brain oscillations in language processing. *Frontiers in Psychology*. https://doi.org/10.3389/fpsyg.2012.00201

Weiss, S., Mueller, H., Schack, B., King, J., Kutas, M., & Rappelsberger, P. (2005). Increased neuronal communication accompanying sentence comprehension. *International Journal of Psychophysiology, 57*(2), 129–141. https://doi.org/10.1016/j.ijpsycho.2005.03.013

Wells, J. B., Christiansen, M. H., Race, D. S., Acheson, D. J., & MacDonald, M. C. (2009). Experience and sentence processing: Statistical learning and relative clause comprehension. *Cognitive Psychology, 58*(2), 250–271. https://doi.org/10.1016/j.cogpsych.2008.08.002

Wernick, J. S., & Starr, A. (1968). Binaural interaction in the superior olivary complex of the cat: An analysis of field potentials evoked by binaural-beat stimuli. *Journal of Neurophysiology, 31*(3), 428–441. https://doi.org/10.1152/jn.1968.31.3.428

Wischnewski, M., Engelhardt, M., Salehinejad, M. A., Schutter, D. J. L. G., Kuo, M. F., & Nitsche, M. A. (2019). NMDA receptor-mediated motor cortex plasticity after 20 Hz transcranial alternating current stimulation. *Cerebral Cortex, 29*(7), 2924–2931. https://doi.org/10.1093/cercor/bhy160

Wiwatwongwana, D., Vichitvejpaisal, P., Thaikruea, L., Klaphajone, J., Tantong, A., & Wiwatwongwana, A. (2016). The effect of music with and without binaural beat audio on operative anxiety in patients undergoing cataract surgery: A randomized controlled trial. *Eye, 30*(11), 1407–1414. https://doi.org/10.1038/eye.2016.160

Wulfeck, B. B. (1988). Grammaticality judgments and sentence comprehension in agrammatic aphasia. *Journal of Speech, Language, and Hearing Research, 31*(1), 72–81. https://doi.org/10.1044/jshr.3101.72

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