Beta and gamma binaural beats enhance auditory sentence comprehension

Hyun-Woong Kim
School of Behavioral and Brain Sciences, The University of Texas at Dallas, Dallas
Jenna Happe
School of Behavioral and Brain Sciences, The University of Texas at Dallas, Dallas
Yune Sang Lee (Yune.Lee@UTDallas.edu)
School of Behavioral and Brain Sciences, The University of Texas at Dallas, Dallas

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Research Article

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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 analysis 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. 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 music-only, especially for syntactically more complex object-relative sentences. To explore if the binaural beat effect can be generalized to another type of language task, we conducted Experiment 2 in which another 100 participants indicated whether or not there was a grammatical error in spoken sentences embedded with a subject- or object-relative clause. 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 (8-12Hz), beta (13–30 Hz), and gamma (> 30Hz) bands (Ala et al., 2018; Beauchene et al., 2016; 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 Garcia-Argibay et al., 2019a for a recent meta-analysis). 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 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., 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; 4-7Hz: Mallik & Russo, 2022; 10 Hz: Wiwatwongwana et al., 2016).

In the present behavioral study, we investigated whether binaural beats facilitate auditory sentence processing, a cognitive domain that has never been explored with this technique. We recruited 200 young adults across two language experiments, 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 minutes prior to performing a language task (Fig. 1C). The exposure duration was chosen based on a recent study showing that 9 minutes 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 spoken sentence comprehension task involving syntactic interpretation of the noun-verb relation (Figure 1C). 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'). Object-relative sentences are more difficult than subject-relative sentences to comprehend due to their syntactically non-canonical structure (Wells et al., 2009; MacDonald & Christiansen, 2002) and their higher demand on working memory (Just & Carpenter, 1992; King & Just, 1991).

We used binaural beats of the theta (7Hz), beta (18 Hz), and gamma (40 Hz) frequency bands because each of these bands has been associated with sentence comprehension in previous research. In particular, coherence of EEG oscillations of the theta, beta, and gamma frequencies was increased in response to object-relative compared to subject-relative sentences (Weiss et al., 2005). Beta and gamma oscillations are thought to mediate core language functions — syntactic and semantic operations respectively during sentence comprehension (Prystauka & Lewis, 2019). For example, 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. Lastly, 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), leading to a conjecture that theta oscillations play a 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 upon sentence-level language processing, 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 compensation. 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 comfortable volume via Sennheiser HD-280 headphones. For the binaural beat stimulation, a pure tone with a frequency of 250 Hz 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 (Figure 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). In the control 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 lighted sound-proof booth.

For the sentence comprehension task, the stimuli were comprised of 128 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 seconds. 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 binaural beat conditions (Figure 1B): music + theta (7 Hz), music + beta (18 Hz), music + gamma (40 Hz), or music only (N= 25 for each condition). Participants were first familiarized with the language task by undergoing 16 practice trials, during which they received feedback after each response. Sentences used during the practice session were never presented during the main experiment. After the practice was completed, participants listened to music mixed with or without binaural beats for 10 minutes while fixating their eyes on a speaker icon on the screen. Participants were not explicitly informed about the presence of binaural beat embedded in the music. Immediately after listening to the sound, participants underwent 64 trials of the sentence comprehension task. A 15-second break was provided every 16 trials. The task duration varied across participants, ranging from 10 to 15 minutes including the breaks. This procedure was repeated with another 64 trials (Figure 1C). No feedback was provided during the two task blocks.

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 statistical significance of the fixed effects was assessed using the Type III Wald chi-square tests of the *car* package (Fox et al., 2012).

Results

As expected, there was a significant main effect of sentence type on accuracy [$\chi^2(1) = 155.66$, $p < .001$], with a lower score in object-relative (M = 77.1%) compared to subject-relative sentences (M = 93.9%). Critically, we found a significant main effect of binaural beat condition [$\chi^2(3) = 8.17$, $p = .043$], 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 control (i.e., music-only) condition (M = 81.0%). We also found a significant interaction [$\chi^2(3) = 18.96$, $p < .001$] due to a more robust binaural beat effect on the object-relative sentences compared to subject-relative sentences (Figure 2).

To further examine the significant interaction effect, we analyzed the accuracy data using the same logistic model between the control group and each of the binaural beat groups within object-relative sentences. The results revealed higher accuracy in the beta (81.8%) [$\chi^2(1) = 4.08$, $p = .043$] and gamma (M = 83.1%) [$\chi^2(1) = 5.27$, $p = .022$] binaural beat groups than in the control group (M = 68.5%). However, the slight increase in theta relative to control did not reach statistical significance (M = 74.8%) [$\chi^2(1) = .87$, $p = .349$].

Experiment 2

The findings in Experiment 1 naturally invite the following questions: could the binaural beat effect be generalized to a different language task during auditory sentence processing? Also, can we observe a differential degree of the binaural beat effects (e.g., only beta, not gamma and vice versa; a newly emerging effect of theta) by employing a different language task? To address these questions, we constructed another set of object-relative and subject-relative sentences, half of which contained a morpho-syntactic error on subject-verb agreement or a verb tense (Table 2). After binaural beat or control stimulation, participants underwent a grammaticality judgment task on the sentences.

For the new task involving grammaticality 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 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 semantically anomalous word 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 syntactic violation studies, theta and/or beta binaural beats would enhance grammaticality judgement 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-none 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 compensation. 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.

Participants were randomly assigned to one of four binaural beat conditions: music + theta (7 Hz), music + beta (18 Hz), music + gamma (40 Hz), or music only (N = 25 for each condition). Participants received 8 practice trials, during which they were given feedback after each response. The sentence materials during the practice were not used for the main experiment. After listening to the music, the participants underwent 48 trials of the grammaticality judgment task. Participants took a 15 second break after every 12 trials. The task duration ranged from 10 to 15 minutes including breaks. This procedure was repeated with another round of the grammaticality judgement task consisting of 48 trials. No feedback was provided during the actual task.

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.

Results

Consistent with the Experiment 1, there was a significant main effect of sentence type on *d'* [$F(1,99)=31.36$, $p < .001$], with lower accuracy on object-relative (M = 1.19) compared to subject-relative (M = 1.51) sentences (Figure 3). Although the group mean accuracy was slightly higher in the three binaural beat groups than in the control group, there was neither a main effect of binaural beat condition [$F(1,99)=1.37$, p = .255] nor a significant interaction [$F(3,99)=.21$, p = .892]. Together, these binaural beats did not yield similar effects as Experiment 1 on another language task involving grammaticality analysis 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 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 beta and gamma binaural beats significantly enhanced the task performance for the object-relative sentences. Experiment 2 was subsequently designed to see if the binaural beat effect could be generalized to another linguistic operation (i.e., grammaticality judgement), which yielded non-significant results. This suggests that the binaural beat effects on auditory sentence processing depend on a specific linguistic operation. In what follows, we discuss the theoretical and practical implications of the current findings.

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 comprehending 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 the working memory for objective-relative sentences, whereas only a single agent is present in subject-relative sentence (King & Just, 1991; see Table 1). Indeed, 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, such a working memory account may not fully account for the finding in Experiment 1, given the lack of beta binaural beat effect in Experiment 2, which presumably required listeners to maintain linguistic elements in a sentence for grammaticality analysis (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 enhancement during sentence comprehension 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). Relatedly, 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 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 the 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 operations are often intertwined and influence each other (e.g., Gámez & Vasilyeva, 2015; Gunter et al., 2000). Unfortunately, the current study design cannot dissociate the functional role of gamma on semantic from syntactic processes, which necessitates a follow-up study.

Another possibility is that gamma binaural beat may have provided an attentional boost given the extensive literature implicating the role of gamma oscillations on attention (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), a 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 a 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 in that attention would be required to successfully detect grammatical errors.

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

Our findings suggest that beta and gamma binaural beats have functional specificity in that 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. 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 their sentence comprehension ability, compared to their grammaticality judgment ability (Justus, 2004). The present results are in line with the view that the ability to construct a syntactic representation for grammaticality judgment is dissociable from the ability to analyze the syntactic relations between words for successful sentence comprehension (Linebarger et al., 1983).

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

Although the theta binaural beat yielded slightly higher accuracy than music-only, the difference did not reach statistical significance in both experiments. Theta oscillations are thought to play a key role in working memory functions, e.g., increased theta power being 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 a theta binaural beat would improve auditory sentence processing by facilitating the domain-general processing. However, our findings indicate that the theta binaural beat is 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 a 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 minutes of theta binaural beat stimulation. As we mentioned earlier, we chose 10 minutes of binaural beat stimulation based upon the evidence that a 9-minute duration was sufficient to induce neural entrainment (Ala et al., 2018; Jirakittayakorn & Wongsawat, 2017). While our study still failed to observe a theta binaural beat effect, Ortiz et al. (2008) found a significant improvement in verbal memory by using 15 minutes of theta binaural beat stimulation. A future study should consider employing a longer theta binaural beat stimulation to test the possibility that a longer duration is required.

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. On one hand, these findings suggest that binaural beats can be practically used along with music as a non-invasive sound therapy. On the other hand, the interaction effect must be explained by follow-up experiments that include a binaural-beat only condition.

Another important question 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 in that binaural beat stimulation was repeated twice for each participant and each task block took less than 15 minutes. From a therapeutic perspective, it would be informative in future studies to establish the duration of binaural beat effects, as is the case with application of neurostimulation (Kasten et al., 2016), such that one can receive an optimal dosage of binaural beat stimulation.

Conclusion

In summary, 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 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. Certainly, future research is warranted 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) as well as 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.

Declarations

Funding information

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Ethics approval

The methodology for this study was approved by the University of Texas at Dallas Institutional Review Board (IRB-21-109).

Competing interests

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

Data availability

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

Author contributions

Conceptualization: Hyun-Woong Kim and Yune Sang Lee; Methodology: Hyun-Woong Kim and Yune Sang Lee; Investigation: Jenna Happe; Formal analysis: Hyun-Woong Kim; Data curation: Hyun-Woong Kim; Writing – original draft: Hyun-Woong Kim and Jenna Happe; Writing – review & editing: Hyun-Woong Kim, Jenna Happe, and Yune Sang Lee; Supervision: Yune Sang Lee.

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Tables

Table 1. Sentence examples used in Experiment 1. The embedded clause is underlined and the target action verb is in bold face.

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

Table 2. Examples used in the grammaticality judgment task (Experiment 2). The embedded clause is underlined and the morpho-syntactic violation is shown as italic in the parenthesis. SVA: subject-verb agreement.

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

Figures

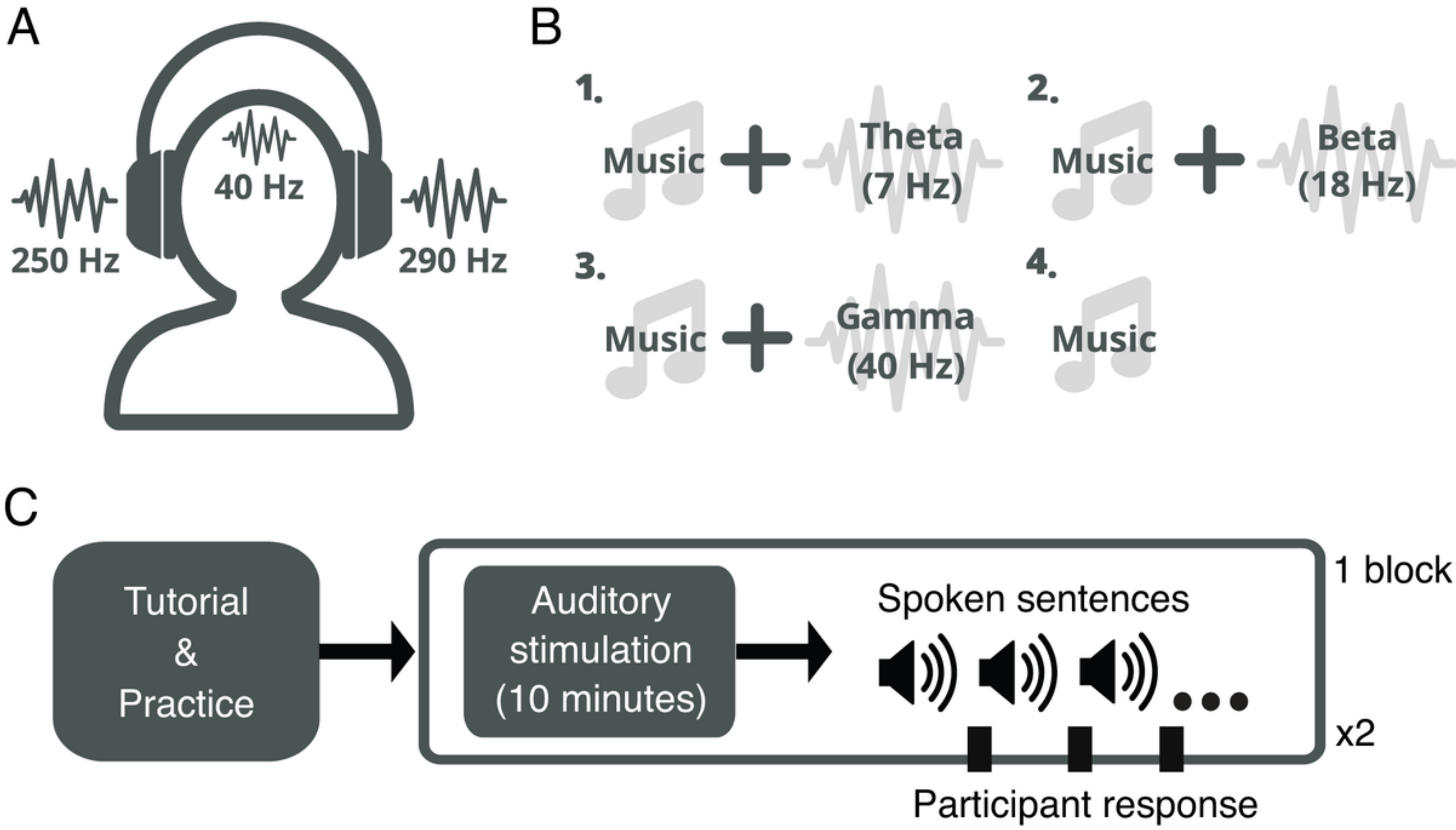

Figure 1

(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 schematic of the experimental procedures. Participants underwent a total of two task blocks.

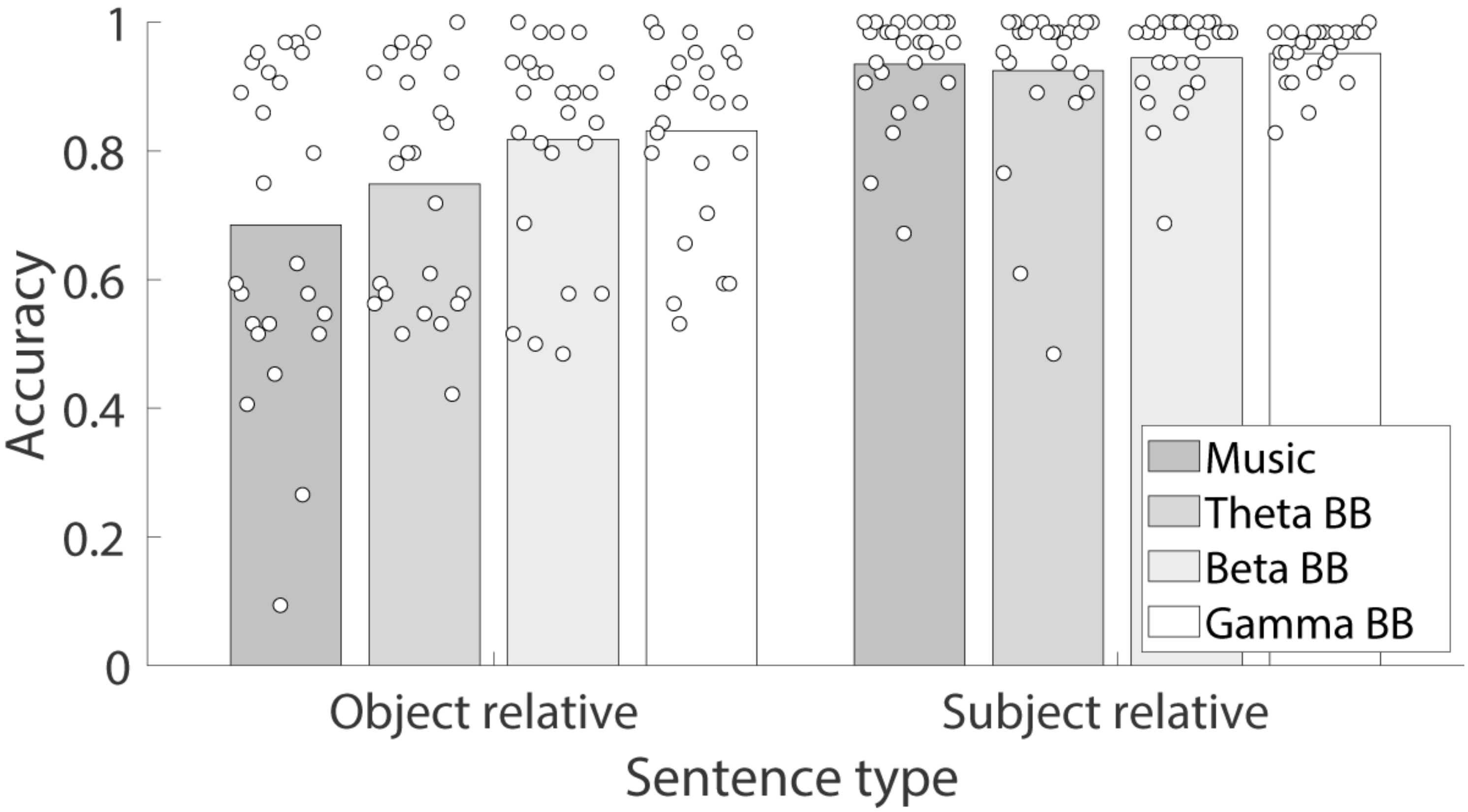

Figure 2

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 music-only group.

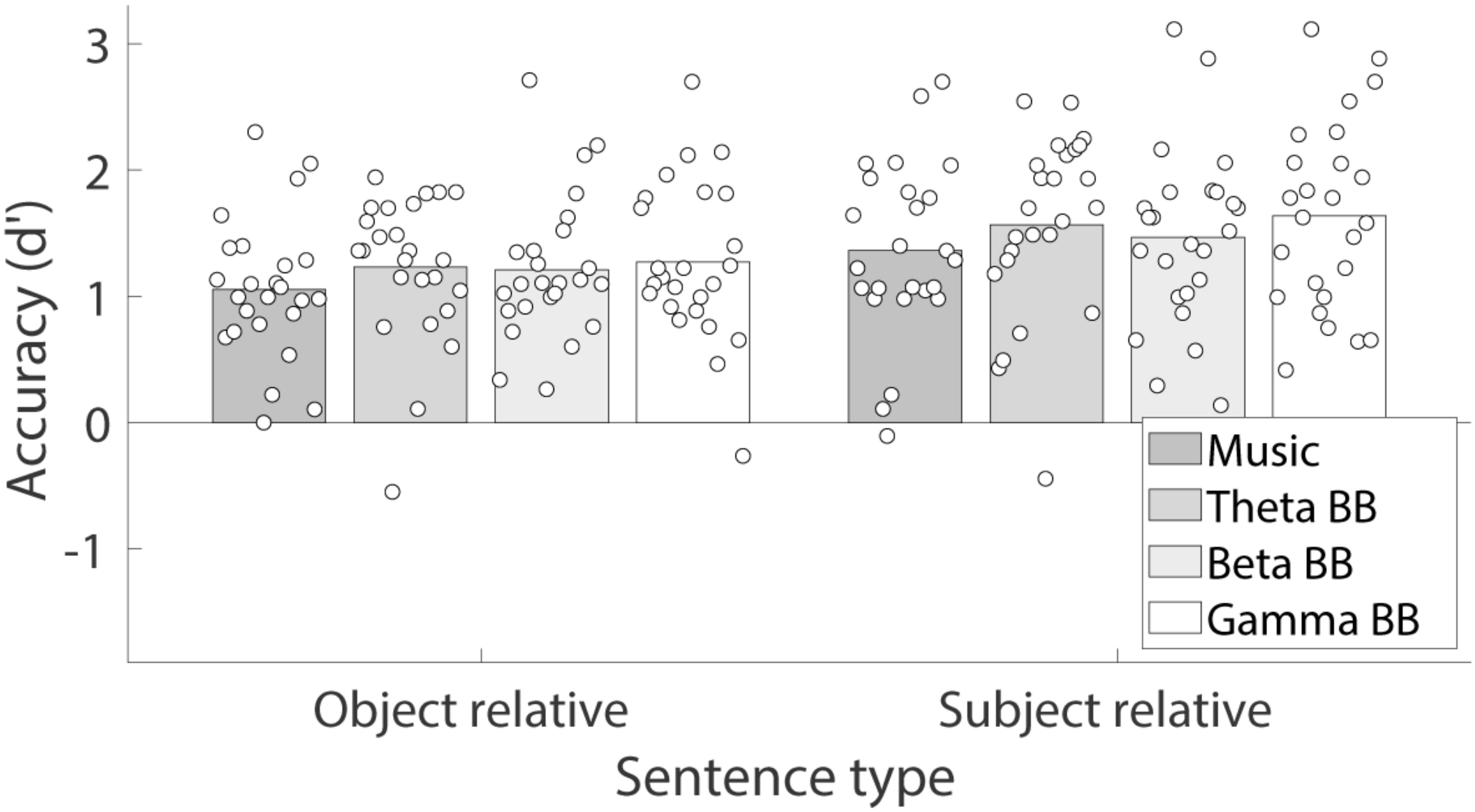

Figure 3

The accuracy of the grammaticality judgment task in the three binaural beat conditions and the music-only condition. Circles indicate individual data points. While participants' performance was lower in the object compared to subject relative condition, it was comparable across all the conditions.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

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