OXFORD

Cerebral Cortex, 2023, 1–9

https://doi.org/10.1093/cercor/bhad459

Original Article

Neural consequences of binaural beat stimulation on auditory sentence comprehension: an EEG study

Jeahong Kim[1,2,†], Hyun-Woong Kim[1,2,3,4,†], Jessica Kovar[1,2], Yune Sang Lee[1,2,3,5,*]

[1]School of Behavioral and Brain Sciences, The University of Texas at Dallas, Richardson, TX 75080, United States,
[2]Callier Clinical Research Center, The University of Texas at Dallas, Richardson, TX 75080, United States,
[3]Center for BrainHealth, The University of Texas at Dallas, Dallas, TX 75235, United States,
[4]Department of Psychology, The University of Texas at Dallas, Richardson, TX 75080, United States,
[5]Department of Speech, Language, and Hearing, The University of Texas at Dallas, 800 W. Campbell Road, Richardson, TX 75080, United States

[*]Corresponding author: Email: Yune.Lee@UTDallas.Edu

[†]Jeahong Kim and Hyun-Woong Kim have contributed equally.

A growing literature has shown that binaural beat (BB)—generated by dichotic presentation of slightly mismatched pure tones—improves cognition. We recently found that BB stimulation of either beta (18 Hz) or gamma (40 Hz) frequencies enhanced auditory sentence comprehension. Here, we used electroencephalography (EEG) to characterize neural oscillations pertaining to the enhanced linguistic operations following BB stimulation. Sixty healthy young adults were randomly assigned to one of three listening groups: 18-Hz BB, 40-Hz BB, or pure-tone baseline, all embedded in music. After listening to the sound for 10 min (stimulation phase), participants underwent an auditory sentence comprehension task involving spoken sentences that contained either an object or subject relative clause (task phase). During the stimulation phase, 18-Hz BB yielded increased EEG power in a beta frequency range, while 40-Hz BB did not. During the task phase, only the 18-Hz BB resulted in significantly higher accuracy and faster response times compared with the baseline, especially on syntactically more complex object-relative sentences. The behavioral improvement by 18-Hz BB was accompanied by attenuated beta power difference between object- and subject-relative sentences. Altogether, our findings demonstrate beta oscillations as a neural correlate of improved syntactic operation following BB stimulation.

Key words: language; sentence comprehension; binaural beat; auditory beat stimulation; EEG; beta frequency; grammar; syntax; cognition; entrainment; performance enhancement.

Introduction

A binaural beat (BB) is a de novo sound that occurs when two slightly mismatched pure tones are dichotically presented. For example, the brain will generate a BB of 20 Hz when 440 and 460 Hz pure tones are presented to left and right ear, respectively. The BB is thought to take place at the level of the superior olivary nuclei in the brainstem (Wernick and Starr 1968; Oster 1973). This phenomenon has been studied for several decades (e.g. Licklider et al. 1950), but it is only recently that the BBs—across multiple frequencies, i.e. theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (>30 Hz)—are on the horizon as a means to improve various cognitive and mental states (for reviews, see Chaieb et al. 2015; Garcia-Argibay et al. 2019a). For example, BB stimulation has been shown to enhance attention (40 Hz: Reedijk et al. 2015; Colzato et al. 2017; Ross and Lopez 2020; Engelbregt et al. 2021), visuospatial and N-back working memory (15 Hz; Beauchene et al. 2016; Beauchene et al. 2017), immediate (5 Hz: Ortiz et al. 2008) and delayed (20 Hz: Garcia-Argibay et al. 2019b) recall of verbal items, and vigilance (16–24 Hz; Lane et al. 1998). In addition, BBs have been used to reduce anxiety (9 Hz: Isik et al. 2017; 4–7 Hz: Mallik and Russo 2022; 10 Hz: Wiwatwongwana et al. 2016).

We have recently explored the potential of BB stimulation in facilitating language processes with healthy young adults (Kim et al. 2023). In this behavioral study, 100 participants were randomly assigned to one of four different listening groups: 18-Hz (beta) BB + music, 40-Hz (gamma) BB + music, 7-Hz (theta) BB + music, and music only as a baseline. Immediately after 10 min of auditory stimulation, they performed a comprehension task requiring prompt analysis on noun–verb relations in spoken sentences containing either a subject-relative (SR) or an object-relative (OR) center-embedded clause. We found that beta and gamma BB, but not theta, yielded significantly better performance than the baseline (music only), especially for syntactically less canonical and more complex OR sentences (Gibson 1998; Levy 2008).

Subsequent to this behavioral finding, we sought to investigate neural correlates of the enhanced sentence comprehension by BB stimulation at beta and gamma frequencies. Previous studies have shown that BB stimulation can entrain neural oscillations to the corresponding beat frequency (Draganova et al. 2008; Pratt et al. 2010; Becher et al. 2015; Beauchene et al. 2016; Jirakittayakorn and Wongsawat 2017; Ala et al. 2018; Lee et al. 2019; Perez et al. 2020), presumably via phase-locking of neuronal excitability to BB (Lakatos et al. 2019). Hence, one testable conjecture is that BB stimulation may lead to better language performance by modulating neural oscillations of specific frequencies pertaining to linguistic operations (Weiss and Mueller 2012; Friederici and Singer 2015; Meyer 2018; Prystauka and Lewis 2019).

In the language domain, both beta- and gamma-band neural oscillations have been implicated in sentence comprehension (Prystauka and Lewis 2019). Beta oscillation is frequently associated with syntactic processing. For example, beta power has

Received: July 17, 2023. **Revised:** November 5, 2023. **Accepted:** November 6, 2023

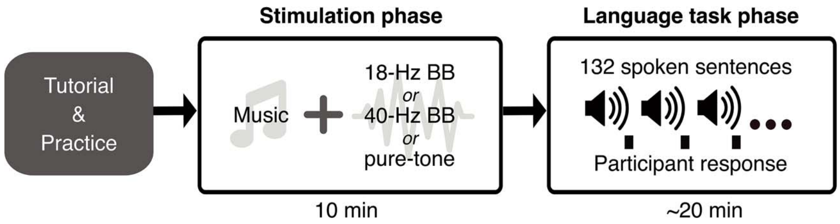

Fig. 1. A schematic of the experimental procedure. Participants were first provided with tutorial and practice for a sentence comprehension task. Then, they underwent auditory stimulation followed by a task phase.

Table 1. Sentence examples in the auditory sentence comprehension task.

Sentence type	Sentence	Answer
Subject relative	Boys that **join** aunts are lucky	Male
Object relative	Boys that aunts **join** are lucky	Female
Subject relative	Aunts that **join** boys are lucky	Female
Object relative	Aunts that boys **join** are lucky	Male

The embedded clauses are underlined, and the target action verbs are in bold.

been shown to increase while reading syntactically well-formed compared with ill-formed sentences (Bastiaansen et al. 2010; Bastiaansen and Hagoort 2015) or listening to sentences with a long compared with a short subject–verb distance (Meyer et al. 2013). In contrast, gamma oscillation has been primarily implicated in studies examining semantic processing while reading or hearing sentences. For example, semantically congruent sentences elicited increased gamma power compared with semantically uninterpretable sentences or word lists (Hald et al. 2006; Bastiaansen and Hagoort 2015), while decreased gamma power was observed in response to semantically anomalous words (Penolazzi et al. 2009; Wang et al. 2012; Rommers et al. 2013). Outside of the language domain, both beta and gamma oscillations have been widely implicated in domain-general cognitive functions, such as memory and attention (Benchenane et al. 2011; Fries 2015; Schmidt et al. 2019).

In the present study, we recorded electroencephalography (EEG) throughout the experiment that began with a BB stimulation phase and ended with a post-stimulation task phase (Fig. 1). Participants were randomly assigned to one of three listening groups: 18-Hz (beta) BB, 40-Hz (gamma) BB, or pure tone (i.e. the same frequency tone played to both ears), all embedded in music. During the task phase, participants listened to a series of SR or OR sentences and were asked to indicate the gender of the agent in each sentence (Table 1).

We formulated the following hypotheses. First, 18- and 40-Hz BBs would elicit higher beta and gamma power, respectively, compared with pure tone, during the stimulation period. Secondly, 18- and 40-Hz BBs would yield better sentence comprehension performance compared with pure tone, particularly for OR sentences, as has been previously observed (Kim et al. 2023). Thirdly and most importantly, we investigated whether the language enhancement from 18- and 40-Hz BB stimulation would be accompanied by modulation of beta-band (i.e. 13–30 Hz) and gamma-band (i.e. 31–45 Hz) oscillatory activities during sentence processing, respectively. Of particular interest is the directionality of beta power; while a previous EEG study reported increased beta power for OR compared with SR sentences (Bastiaansen and Hagoort 2006), other studies showed the opposite pattern, with decreased beta power in response to OR than SR sentences (Meltzer and Braun 2011; Lewis et al. 2016, 2023). For the 40-Hz BB, although gamma power has yet been implicated during the relative clause processing (but see Weiss et al. 2005 for EEG coherence results), we expected that 40-Hz BB stimulation would modulate gamma power during the language task—especially for syntactically more complex OR condition—to keep up with the task demand.

Materials and methods

Participants

Sixty-three volunteers participated in the study for monetary compensation or course credits (mean age = 24.6 years, *SD* = 2.7 years, range = 18–35 years; 14 females; all right-handed). All participants reported normal or corrected-to-normal vision and no history of psychiatric or neurological disorders. Two participants were excluded from the further analyses due to poor behavioral task performance (i.e. accuracy < 3 *SD* from the mean) and another was excluded due to poor EEG signals, leaving a total of 60 intact participants' data. Participants gave their informed online consent prior to the study. The study protocol was approved by the Institutional Review Board of the University of Texas at Dallas (IRB-21-19) and conducted in accordance with the Declaration of Helsinki. All methods were carried out in agreement with the relevant guidelines and regulations.

Stimuli and procedures

All auditory stimuli were delivered through electromagnetic radiation-free stereo earphones (DefenderShielder) at a comfortable volume which was adjusted for individual participants. None of the participants reported an issue with hearing music and sentences. Each participant was randomly assigned to one of three listening groups ($n = 20$ per each): 18-Hz BB (*L:250 Hz; R: 268 Hz*), 40-Hz BB (*L:250 Hz; R: 290 Hz*), and pure-tone baseline (*L:250 Hz; R: 250 Hz*). Two pure tones were embedded in an excerpt of slow-tempo, nonrhythmical music (Dangol 2019; Kim et al. 2023), at a beat-to-music ratio of −2 dB. Auditory sentence stimuli were generated using the Google Text-to-Speech with the speaker voice set to an American-English speaking male.

The language materials for the sentence comprehension task consisted of 132 English spoken sentences, each containing a male noun, a female noun, a transitive action verb, and an adjective (Table 1). Each sentence was center-embedded with either a subject relative (SR) or an object relative (OR) clause. The two sentence types (i.e. SR and OR sentences) only differed in the order of the noun and the verb within the relative clause, which determined the meaning of a sentence (Table 1). Note that, in OR sentences, the individuals performing an action (e.g. join) are different from those described by an adjective (e.g. lucky), whereas in SR sentences, those are the same. Such mismatch may further make the comprehension of OR sentences more difficult. These sentence stimuli were equalized in root-mean-square intensity. In the task, participants listened to a spoken sentence and indicated the gender of the individuals performing an action as quickly and accurately as possible within 2 s from the offset of each sentence by pressing either the "male" (d) or "female" (g) button on the keyboard with the left hand. The sentence type (i.e. SR and OR) and the gender of the agent (i.e. male or female) were counterbalanced across the 132 sentences.

As depicted in Fig. 1, participants first underwent a practice session consisting of 12 trials, for which feedback was provided. Participants then underwent another practice session with the same 12 trials. If participants' accuracy was lower than 80% on either of the two practice sessions, they continued repeating the practice session with the same 12 trials until achieving an accuracy of over 80% in two sessions (these did not have to be consecutive). After the practice session, participants proceeded to the stimulation phase lasting 10 min. They were instructed to close their eyes, avoid body movement, and pay attention to the sound during this period. The stimulation phase was immediately followed by the language task phase. In each trial, participants were instructed to refrain from eye-blinking and to hold a response until the sentence ended. An eye-blink prompt was presented for 2 s after each response. Participants were trained on the eye-blinking instruction during the practice. The experimental instruction, stimuli, and response collection for auditory stimulation and sentence comprehension task were controlled using PsychoPy3 (Peirce 2007). The experiment took ∼1.5 h, including EEG preparation.

Behavioral data analysis

For the (binary) accuracy data, we used a generalized logistic linear mixed-effect (LME) model. An LME model was instead used for (continuous) reaction time data obtained from correct trials. We used the lme4 packages (Bates et al. 2015) in R (ver 2022.07.0 + 548). The model included two fixed effects of sentence type (SR vs. OR) and listening group (18-Hz BB, 40-Hz BB, and pure-tone baseline) as well as two random intercepts of participants and items. We report statistical significance of the fixed effect using the Type III Wald chi-square test of the *car* package (Fox et al. 2012). We used a two-sided general linear hypothesis test (glht) of the *multcomp* package (Hothorn et al. 2016) to examine the difference in accuracy and reaction time between each of the two BB groups and the baseline group, following a significant interaction effect.

EEG recording

EEG was recorded using Neuroscan SynAmps 2 amplifier with the CURRY-8 Neuroimaging Suite Software and 64 Ag-AgCl electrodes mounted Quik-Cap Neo Net (Neuroscan Inc.). A reference electrode was positioned between Cz and CPz, while a ground electrode was placed between FPz and Fz. Additionally, bipolar vertical (above and underneath the left eye) and horizontal (left and right of the eyes) electrooculograms (EOGs) were recorded to monitor eye-blinks and eye-movements, respectively. All impedances were kept below 5 kΩ. EEG data were collected at a sampling rate of 1,000 Hz, high-pass filtered at 0.1 Hz, and low-pass filtered at 400 Hz.

EEG preprocessing pipeline

Raw EEG signals were preprocessed using EEGlab toolbox v14.1.1 (Delorme and Makeig 2004) in Matlab 2021b (Mathworks, Inc.). All EEG signals were resampled at 250 Hz and bandpass filtered using Butterworth impulse response function (cut-off at 0.1 and 58 Hz). Bad channels containing high spectrum variation (i.e. greater than 5 *SD*) were removed using the *pop_rejchan* function in the EEGlab. Independent component analysis (ICA) was performed on the continuous EEG signal for each participant, and the artifact ICA components associated with eye-blinks, movement, and muscle activity were removed using the ICLABEL (MARA; Pion-Tonachini et al. 2019). The post-ICA EEG data were adjusted using the Common Average Reference scheme, in which the mean EEG signal across 64 channels was subtracted from each channel's signal.

For the EEG data recorded during the stimulation phase, the EEG signals were segmented into the first 3 min, the middle 3 min, and the last 3 min, each of which was subsequently segmented into consecutive 2-s epochs. The EEG signals obtained during the task phase were segmented from −500 to +1,800 ms with respect to the onset of the relative pronoun (i.e. "that") of each sentence. For the baseline correction, the EEG amplitude averaged from −100 to 0 ms was subtracted from the EEG amplitudes of the range (i.e. −500 to +1800 ms) of each epoch. Spherical interpolation was used to recover the bad channels from the EEG signals for both phases. After segmenting the epochs, artifact rejections were further performed using the following parameters: the lowest activity trend of 0.05 μV; the highest activity trend of 50 μV; and the range of allowed amplitude between −100 and + 100 μV. On average, 88% and 85% of data remained after the artifact rejection procedure for stimulation and language task EEGs, respectively. After artifact rejection, 83.4 (*SD* = 8.3), 84.8 (*SD* = 6.4), and 84.2 (*SD* = 7.3) epochs survived for the first, middle, and last 3-min periods during the stimulation phase, respectively. For the task phase, 51.9 (*SD* = 8.4) and 53.7 (*SD* = 7.2) epochs were entered into data analyses for the OR and SR sentence conditions, respectively.

Finally, each of the cleaned epochs was transformed to the frequency domain using a short-time Fourier transform via the Fieldtrip toolbox (Maris and Oostenveld 2007), yielding a time–frequency spectrum of signal amplitude (μV) with a frequency width of 2 Hz for smoothing (0.5-Hz steps) and a sliding time window of 500 ms (20-ms steps) multiplied with a Hanning taper. Note that there is inherent trade-off between time and frequency resolutions, with better time resolution at the expense of reduced frequency resolution, and vice versa. Here, we chose 500 ms as a fixed time window based on a recent study that also used sentences containing relative clauses (Lewis et al. 2023). For the task phase data, we normalized the EEG power signals for each condition and participant by calculating relative power changes with respect to the mean power during the baseline period (−440 to 0 ms). The baseline range was defined as the averaged interval from the onset of the first word to the occurrence of pronoun "that" (i.e. 440 ms) in a given sentence.

Cluster-based permutation analysis

To investigate the entrainment effects of 18- and 40-Hz BBs on the EEG power during the stimulation phase, we first calculated two neural entrainment indices (NEI), one by subtracting the averaged power of the first 3-min from the middle 3-min (mid-NEI), and the other by subtracting that of the first 3-min from the last 3-min (late-NEI), per each of the listening groups. We then compared the NEI between 18-Hz BB vs. baseline as well as 40-Hz BB vs. baseline, using a cluster-based permutation procedure in the Fieldtrip toolbox (Maris and Oostenveld 2007), in the beta (13–30 Hz) and the gamma (31–45 Hz) ranges, respectively. The size of the frequency-electrode cluster was determined by triangulation parameters in the Fieldtrip, and a minimum of two neighboring frequencies and channels constituted each cluster. A cluster-level test statistic was then calculated by summing all the *t*-values from independent *t*-tests within each frequency-electrode cluster. The significance of each cluster was assessed using a Monte Carlo method, wherein the analysis was repeated 10,000 times, each with new random labels. The significance was determined with $P < 0.05$.

To examine the neural oscillations during the auditory sentence comprehension task, we calculated a syntactic difference index (SDI) by subtracting the average power change of SR from OR sentences for each group. We then performed cluster-based permutation tests to determine the significance of SDI difference between 18-Hz BB vs. baseline as well as 40-Hz BB vs. baseline, across the time points from 0 to 1200 ms at all electrodes. For the former comparison, three beta bands of interest, i.e. β_1 (13–18 Hz), β_2 (19–25 Hz), and β_3 (26–30 Hz) were chosen as frequencies of interest in a post hoc manner based upon a review article (Weiss and Mueller 2012), which described results at each of the three beta subbands including beta1 (e.g. Bastiaansen et al. 2010), beta2 (e.g. Luo et al. 2010), and beta3 (e.g. Shahin et al. 2009). For the latter, we opted to use γ_1 (31–34 Hz), γ_2 (35–40 Hz), and γ_3 (41–45 Hz), based on the previous finding that showed a significant coherence difference between OR and SR sentences in a low gamma range (30–34 Hz; Weiss et al. 2005). Upon significant group differences, we examined the SDI separately for each group, using cluster-based permutation paired *t*-tests. Throughout comparisons of the task phase data, the aforementioned analytic procedure was also used.

Results

Stimulation phase

When the mid-NEI was compared between the 18-Hz BB and baseline groups, we found a significant difference in the β_1 band (15–16 Hz) in the left posterior and anterior electrodes ($P = 0.020$) due to significant increase in NEI in the 18-Hz BB group ($t(19) = 3.31$, $P = 0.004$) and decrease in the baseline group ($t(19) = -4.31$, $P < 0.001$) (Fig. 2A). In contrast, a significant increase in the late-NEI emerged in the β_2 band (22.5–23 Hz) in the left anterior electrodes ($P = 0.049$) during the stimulation phase (Fig. 2B). As can be seen in Fig. 2D, the EEG power was increased in the 18-Hz BB group ($t(19) = 2.99$, $P = 0.008$), while it was decreased in the baseline group ($t(19) = -2.54$, $P = 0.020$) after stimulation. When the NEI was compared between the 40-Hz BB and baseline groups, we found no significant differences in NEI.

Task phase

Behavioral data

Figure 3A shows the accuracy of the behavioral performance. For the accuracy data, we found a significant main effect of sentence type ($\chi^2(1) = 40.99$, $P < 0.001$), with a higher score in SR sentences ($M = 98.2\%$) than in OR sentences ($M = 92.4\%$). The main effect of listening group was marginally significant ($\chi^2(3) = 5.98$, $P = 0.050$), with higher accuracy in the 18-Hz BB ($M = 97.1\%$) and the 40-Hz BB ($M = 95.2\%$) groups than in the baseline group ($M = 93.6\%$). The interaction effect between sentence type and group was also marginally significant ($\chi^2(3) = 5.98$, $P = 0.064$), indicating that the group effect was more pronounced in OR sentences. Post-hoc comparisons between the three groups for OR sentences showed that accuracy was significantly higher in the 18-Hz BB group ($M = 95.5\%$) than the baseline group ($M = 89.2\%$) ($z = 2.42$, $P = 0.026$). Although accuracy was numerically higher in the 40-Hz BB group ($M = 92.5\%$) than the baseline, the difference was not statistically significant ($z = 0.83$, $P = 0.408$).

For the response time data, there was a significant main effect of sentence type ($\chi^2(1) = 30.80$, $P < 0.001$), with faster response in SR sentences ($M = 921$ ms) than in OR sentences ($M = 1176$ ms). We also found a significant main effect of group ($\chi^2(3) = 7.42$, $P = 0.024$), with faster response in the 18-Hz BB ($M = 889$ ms) and 40-Hz BB ($M = 997$ ms) than in the baseline group ($M = 1258$ ms). Importantly, an interaction effect between two factors was significant ($\chi^2(3) = 16.68$, $P < 0.001$), indicating a more robust BB effect on OR compared with SR sentences. We further compared response time between 18-Hz BB vs. baseline and 40-Hz BB vs. baseline within OR sentences. Response time was significantly faster in the 18-Hz BB group ($M = 973$ ms) than the baseline group ($M = 1446$ ms) ($z = 2.63$, $P = 0.027$). As is the case with the accuracy, the response time of 40-Hz BB group ($M = 1109$ ms) was numerically faster than the baseline, but it did not survive significance ($z = 1.94$, $P = 0.123$).

EEG data

When the SDI (i.e. OR minus SR EEG power) was compared between the 18-Hz BB and baseline groups, a significant difference emerged in β_2 power at the time window of 680–840 ms in the left anterior electrodes ($P = 0.046$; Fig. 4A). In contrast, we found no difference in SDI when the 40-Hz BB and baseline groups were compared in any of γ_1, γ_2, and γ_3 power. To further examine the significant group effect on SDI, we examined the β_2 power changes within the 18-Hz BB and baseline groups separately. As can be seen in Fig. 4B and C, higher β_2 power change was observed for OR compared with SR sentences in the baseline group, specifically at the time window of 680–780 ms in the left anterior electrodes ($P = 0.033$). In contrast, there was no such difference between OR and SR sentences in β_2 power in the 18-Hz BB group.

Discussion

This EEG study sought to determine the neural consequence of BB stimulation on auditory sentence comprehension. We found that 18-Hz BB stimulation elicited increased EEG power toward the end of the stimulation phase at 22.5 and 23 Hz—parts of the β_2 frequency (i.e. 19–25 Hz)—in the left anterior region, while the control pure-tone stimulation elicited decreased EEG power in the same frequency-electrodes. During the subsequent auditory sentence comprehension task, the 18-Hz BB yielded higher accuracy and faster reaction times than did the pure-tone, particularly for syntactically more complex OR sentences. Such behavioral improvement was accompanied by modulation of β_2 power in a consistent location, i.e. the left anterior region, that was independently found during the stimulation phase, further confirming the impact of 18-Hz BB stimulation on syntactic processing within the left frontal area. Importantly, the entrainment induced by 18-Hz BB stimulation was manifested as substantial attenuation of power difference between SR and OR conditions. In contrast, we found no significant neural and behavioral effects induced by 40-Hz BB stimulation. In what follows, we elaborate these findings in more detail.

Previous studies have shown that BB stimulation gives rise to neural entrainment across multiple frequency bands (e.g. Perez et al. 2020). Our results are partially consistent with the extant data, in that 18-Hz BB stimulation increased EEG power at beta frequencies, while there was no significant change in gamma power following 40-Hz BB stimulation. This may indicate that neural entrainment at a gamma range is more difficult to induce than at a beta range with the current sample size ($n = 20$ per

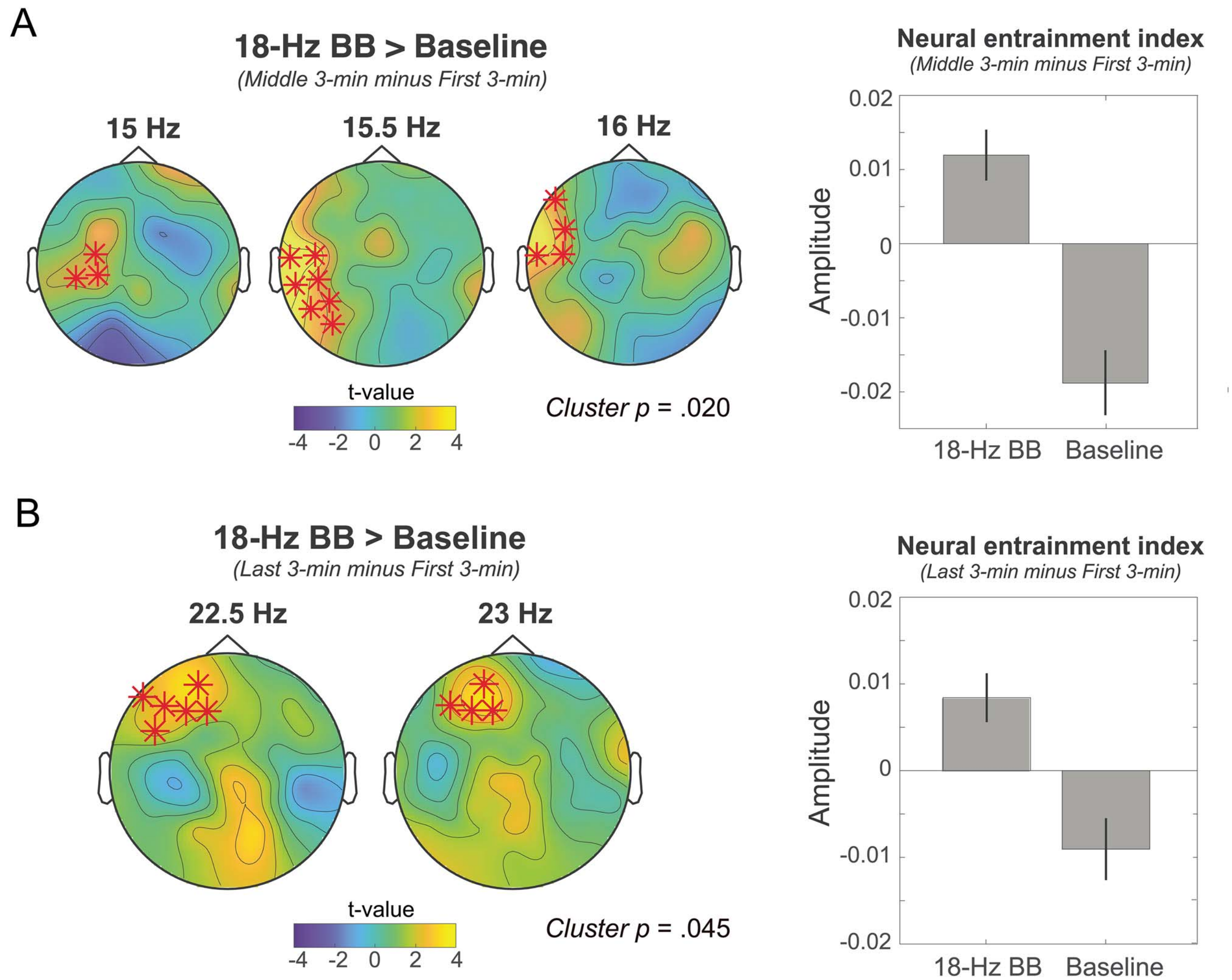

Fig. 2. A and B, left) EEG topography of difference in NEI between the 18-Hz BB and the baseline groups at frequencies exhibiting significant group differences. Asterisks denote electrodes that show a significant difference in NEI. A and B, right) Bar plot displays NEI calculated from the significant frequencies and electrodes. Error bars indicate SEM.

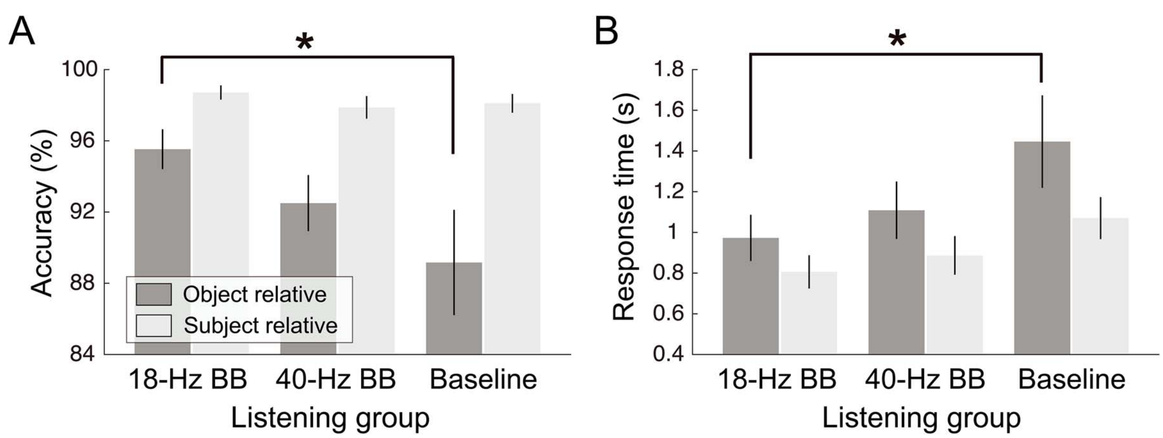

Fig. 3. Behavioral results of A) mean accuracy rate and B) mean response time of auditory sentence comprehension task. Error bars indicate SEM.

each listening group). Intriguingly, the 18-Hz BB enhanced neural oscillations at slightly lower (i.e. 15–16 Hz) or higher (i.e. 22.5–23 Hz) frequencies, albeit within the same beta band. Such cross-frequency entrainment via BB stimulation has been demonstrated in previous work, a characteristic which was not observed using monaural beats (Perez et al. 2020; Engelbregt et al. 2021). Surely, the underlying mechanism of how BB stimulation entrains brain oscillations at different frequencies, as well as the lack of a gamma entrainment effect, deserve further research endeavors. The neuroscience research of BB stimulation is still in its infancy.

Next, we turn to our findings of behavioral and EEG data pertaining to the task phase. Consistent with our previous work

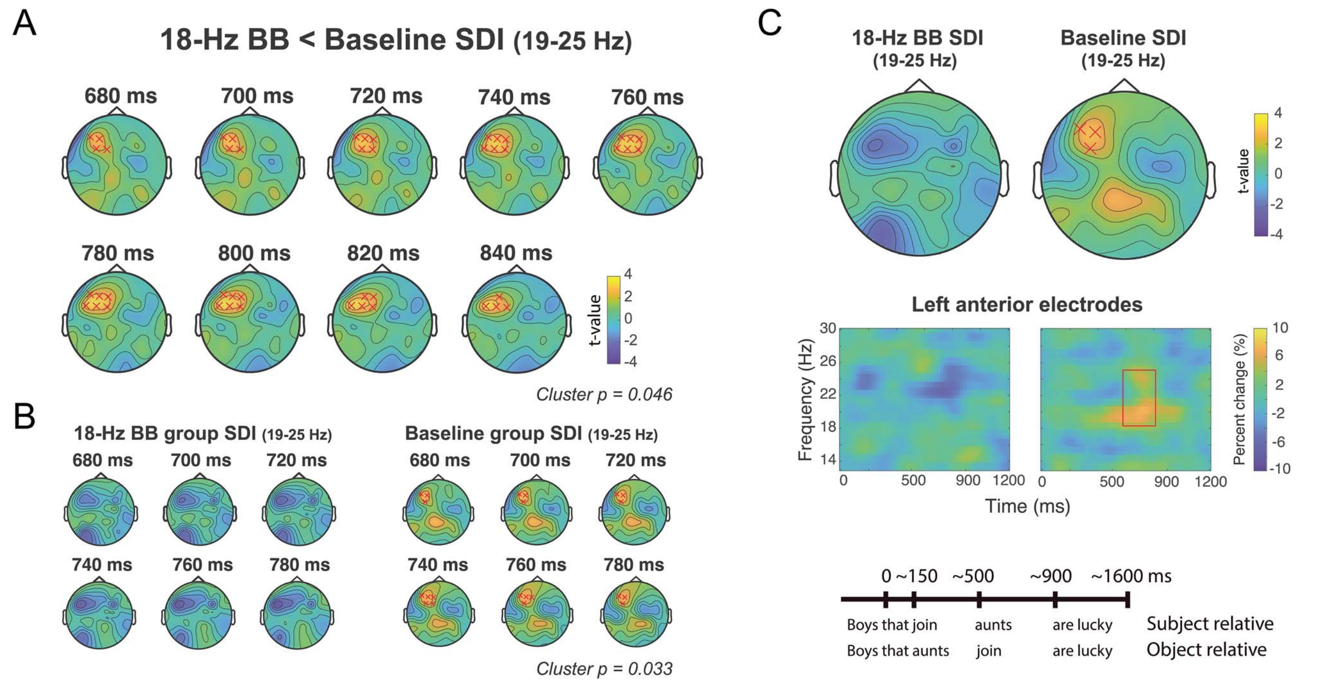

Fig. 4. A and B) EEG topographies of the contrast in SDI (i.e. power difference between OR and SR) between the 18-Hz BB vs. the baseline groups (A) and of SDI in the 18-Hz BB (B, left) and the baseline groups (B, right), all in the β_2 (19–25 Hz) range. C) EEG topographies (top) and time–frequency plots (bottom) of SDI averaged across the time window and the electrodes showing significant baseline SDI differences, for the 18-Hz BB (left) and the baseline groups (right). Asterisks indicate electrodes that show a significant group difference in SDI (A) or a significant SDI in the baseline group (B and C). The box in the time-frequency plot indicates the time window showing a significant SDI.

(Kim et al. 2023), we observed a significant improvement in language task performance for syntactically more complex OR sentences following 18-Hz BB stimulation. Nevertheless, we failed to replicate the 40-Hz BB stimulation effect in the current study. Such discrepancy could be attributed to a difference in sentence stimuli. That is, sentence materials were more complex in the previous study such that each sentence contained two verbs (e.g. "Gentlemen that ladies help adore children." or "Gentlemen that help ladies adore children."), with one serving as a target ("help") and the other being a nontarget ("adore"). This necessarily increased task demand on working memory and/or attention as well as semantic demand, compared with the sentences in the present study that include only one action verb (e.g. Boys that join aunts are lucky; see Table 1). Given that gamma band oscillations have been primarily implicated in semantic rather than syntactic operations (Penolazzi et al. 2009; Wang et al. 2012; Rommers et al. 2013), participants may have benefited from listening to 40-Hz BB more greatly in the previous study than the current study. In other words, we may have observed only a trending effect of 40-Hz BB due to the lack of domain-general and/or semantic demand in the present study. A follow-up study with systematic semantic manipulation is necessary to address this possibility.

Relatedly, 18-Hz BB stimulation was more beneficial for OR than SR sentences, resulting in smaller difference in both accuracy and response time between the two sentence types. To parallel the behavioral data, we calculated a "neural" SDI by obtaining difference in EEG power between OR and SR conditions. Indeed, the SDI mirrored the behavioral pattern, such that the neural index at the β_2 range was significantly smaller in the 18-Hz BB group than the baseline group. This suggests that 18-Hz BB stimulation induced neural entrainment within the β_2 range during the stimulation phase, which may in turn have reduced the SDI in the β_2 range.

Of note, the SDI pattern in the baseline condition was not consistent with previous EEG studies that have shown decreased beta power for OR vs. SR sentences (Meltzer and Braun 2011; Lewis et al. 2016, 2023). Such a decrease in beta power has been interpreted as a disruption of maintaining sentence-level representations due to the less canonical (and thus less predictable) nature of OR sentences (Lewis et al. 2016, 2023). However, it should be noted that, in the current study, the SR and OR sentences were presented with fixed sentence structures (see Table 1), which were relatively short and simple compared with those used in the previous work (e.g. Meltzer and Braun 2011). Moreover, given that the fixed sentence structures were repeated throughout the language task, the OR sentences may not have been so unpredictable compared with the SR sentences. The remaining feature of the OR condition shall be its higher syntactic complexity (Gibson 1998). Such demand in maintaining the OR sentence representation likely yielded higher beta power. Alternatively, the higher beta power for OR than SR sentences may reflect greater demand on attention and/or working memory (King and Just 1991; Just and Carpenter 1992). In either case, the current study demonstrates that the attenuation of SDI in the beta band in the 18-Hz BB group may be a neural correlate of the language enhancement from 18-Hz BB stimulation. This finding naturally invites further questions regarding the functional role of beta frequency during on-line sentence processing.

The beta band modulation was observed at about 600–800 ms after the onset of "that" in the sentences, which roughly corresponded to the second word of the relative clause (Fig. 4). This time window aligns well with that in previous studies reporting beta-band power modulations using syntactic violations (Davidson and Indefrey 2007; Pérez et al. 2012; Schneider et al. 2016), as well as that of P600—a hallmark EEG component of syntactic operation (Friederici 2004; Leckey and Federmeier 2020).

Moreover, in the baseline group, the EEG power topography revealed significant beta modulation in the left anterior region, an area well-established as a part of the core syntactic network (Embick et al. 2000; Bornkessel et al. 2005; Grodzinsky and Friederici 2006; Hagoort and Indefrey 2014; Lee et al. 2022). Consistent with this finding, it has been shown that anodal transcranial direct current stimulation (tDCS) at the left lateral prefrontal cortex or the left inferior frontal gyrus improves sentence comprehension (Hussey et al. 2015; Vergallito et al. 2020). The tDCS technique has gained increasing attention as a therapeutic tool to elicit prolonged changes in the brain, especially for aphasia (Monti et al. 2013). For instance, Marangolo et al. (2011) found that anodal tDCS at the left inferior frontal gyrus daily for a week resulted in improved word repetition performance compared with a week of sham stimulation in patients with chronic aphasia.

In sum, this is the first EEG study demonstrating a neural correlate of beta BB stimulation that resulted in enhanced sentence comprehension performance especially when syntactic complexity was high. From a clinical standpoint, our findings may pave the way for future studies to investigate the potential of beta-band BB stimulation as a therapeutic option for people who have grammar deficits including developmental language disorder and primary progressive aphasia. Certainly, more systematic and empirical validation is required to determine the practical application of BB stimulation in the language domain.

Acknowledgments

We thank the two anonymous reviewers for their helpful comments on the manuscript.

Author contributions

Jeahong Kim (Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing), Hyun-Woong Kim (Conceptualization, Methodology, Visualization, Writing—original draft, Writing—review & editing), Jessica Kovar (Investigation, Writing—review & editing), and Yune Sang Lee (Conceptualization, Funding acquisition, Project administration, Supervision, Writing—original draft, Writing—review & editing)

Funding

This work was supported in part by Digisonic Inc. and the Neuroscience Innovation Foundation.

Conflict of interest statement: The authors have no conflict of interest.

Data availability

The raw data and processing scripts are available at https://doi.org/10.5061/dryad.9zw3r22n5.

References

Ala TS, Ahmadi-Pajouh MA, Nasrabadi AM. Cumulative effects of theta binaural beats on brain power and functional connectivity. *Biomed Signal Process Control*. 2018:42:242–252.

Bastiaansen M, Hagoort P. Oscillatory neuronal dynamics during language comprehension. *Progress in Brain Res*. 2006:159:179–196.

Bastiaansen M, Hagoort P. Frequency-based segregation of syntactic and semantic unification during online sentence level language comprehension. *J Cogn Neurosci*. 2015:27(11):2095–2107.

Bastiaansen M, Magyari L, Hagoort P. Syntactic unification operations are reflected in oscillatory dynamics during on-line sentence comprehension. *J Cogn Neurosci*. 2010:22(7):1333–1347.

Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *J Stat Soft*. 2015:67(1):1–48.

Beauchene C, Abaid N, Moran R, Diana RA, Leonessa A. The effect of binaural beats on visuospatial working memory and cortical connectivity. *PLoS One*. 2016:11(11):e0166630.

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

Becher A-K, Höhne M, Axmacher N, Chaieb L, Elger CE, Fell J. Intracranial electroencephalography power and phase synchronization changes during monaural and binaural beat stimulation. *Eur J Neurosci*. 2015:41(2):254–263.

Benchenane K, Tiesinga PH, Battaglia FP. Oscillations in the prefrontal cortex: a gateway to memory and attention. *Curr Opin Neurobiol*. 2011:21(3):475–485.

Bornkessel I, Zysset S, Friederici AD, Von Cramon DY, Schlesewsky M. Who did what to whom? The neural basis of argument hierarchies during language comprehension. *Neuro Image*. 2005:26(1): 221–233.

Chaieb L, Wilpert EC, Reber TP, Fell J. Auditory beat stimulation and its effects on cognition and mood states. *Front Psychiatry*. 2015:6:70.

Colzato LS, Barone H, Sellaro R, Hommel B. More attentional focusing through binaural beats: evidence from the global–local task. *Psychol Res*. 2017:81(1):271–277.

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

Davidson DJ, Indefrey P. An inverse relation between event-related and time–frequency violation responses in sentence processing. *Brain Res*. 2007:1158:81–92.

Delorme A, Makeig S. EEGLAB: an open-source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J Neurosci Methods*. 2004:134(1):9–21.

Draganova R, Ross B, Wollbrink A, Pantev C. Cortical steady-state responses to central and peripheral auditory beats. *Cereb Cortex*. 2008:18(5):1193–1200.

Embick D, Marantz A, Miyashita Y, O'Neil W, Sakai KL. A syntactic specialization for Broca's area. *PNAS*. 2000:97(11):6150–6154.

Engelbregt H, Barmentlo M, Keeser D, Pogarell O, Deijen JB. Effects of binaural and monaural beat stimulation on attention and EEG. *Exp Brain Res*. 2021:239(9):2781–2791.

Fox J, Weisberg S, Adler D, Bates D, Baud-Bovy G, Ellison S, Firth D, Friendly M, Gorjanc G, Graves S, et al. *Package 'car'*. Vienna: R Foundation for Statistical Computing; 2012 p. 16

Friederici AD. Event-related brain potential studies in language Curr. *Neurol Neurosci Rep*. 2004:4(6):466–470.

Friederici AD, Singer W. Grounding language processing on basic neurophysiological principles. *Trends Cogn Sci*. 2015:19(6):329–338.

Fries P. Rhythms for cognition: communication through coherence. *Neuron*. 2015:88(1):220–235.

Garcia-Argibay M, Santed MA, Reales JM. Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: a meta-analysis. *Psychol Res*. 2019a:83(2):357–372.

Garcia-Argibay M, Santed MA, Reales JM. Binaural auditory beats affect long-term memory. *Psychol Res*. 2019b:83(6):1124–1136.

Gibson E. Linguistic complexity: locality of syntactic dependencies. *Cognition*. 1998:68(1):1–76.

Grodzinsky Y, Friederici AD. Neuroimaging of syntax and syntactic processing. *Curr Opin Neurobiol*. 2006:16(2):240–246.

Hagoort P, Indefrey P. The neurobiology of language beyond single words. *Annu Rev Neurosci*. 2014:37(1):347–362.

Hald LA, Bastiaansen MCM, Hagoort P. EEG theta and gamma responses to semantic violations in online sentence processing. *Brain Lang*. 2006:96(1):90–105.

Hothorn T, Bretz F, Westfall P, Heiberger RM, Schuetzenmeister A, Scheibe S, Hothorn MT. *Package 'multcomp'. Simultaneous inference in general parametric models*. Vol. 66. Vienna, Austria: Project for Statistical Computing; 2016 p. 5565

Hussey EK, Ward N, Christianson K, Kramer AF. Language and memory improvements following tDCS of left lateral prefrontal cortex Antal A, editor. *PLoS One*. 2015:10(11):e0141417.

Isik BK, Esen A, Büyükerkmen B, Kilinç A, Menziletoglu D. Effectiveness of binaural beats in reducing preoperative dental anxiety. *Br J Oral Maxillofac Surg*. 2017:55(6):571–574.

Jirakittayakorn N, Wongsawat Y. Brain responses to 40-Hz binaural beat and effects on emotion and memory. *Int J Psychophysiol*. 2017:120:96–107.

Just MA, Carpenter PA. A capacity theory of comprehension: individual differences in working memory. *Psychol Rev*. 1992:99(1): 122–149.

Kim H-W, Happe J, Lee YS. Beta and gamma binaural beats enhance auditory sentence comprehension. *Psychol Res*. 2023:87: 2218–2227.

King J, Just MA. Individual differences in syntactic processing: the role of working memory. *J Mem Lang*. 1991:30(5):580–602.

Lakatos P, Gross J, Thut G. A new unifying account of the roles of neuronal entrainment. *Curr Biol*. 2019:29(18):R890–R905.

Lane JD, Kasian SJ, Owens JE, Marsh GR. Binaural auditory beats affect vigilance performance and mood. *Physiol Behav*. 1998:63(2): 249–252.

Leckey M, Federmeier KD. The P3b and P600(s): positive contributions to language comprehension. *Psychophysiology*. 2020:57(7):e13351.

Lee M, Song C-B, Shin G-H, Lee S-W. Possible effect of binaural beat combined with autonomous sensory meridian response for inducing sleep. *Front Hum Neurosci*. 2019:13:425.

Lee YS, Rogers CS, Grossman M, Wingfield A, Peelle JE. Hemispheric dissociations in regions supporting auditory sentence comprehension in older adults. *Aging Brain*. 2022:2:100051.

Levy R. Expectation-based syntactic comprehension. *Cognition*. 2008:106(3):1126–1177.

Lewis AG, Schoffelen JM, Schriefers H, Bastiaansen M. A predictive coding perspective on beta oscillations during sentence-level language comprehension. *Front Hum Neurosci*. 2016:3(10): 85.

Lewis AG, Schoffelen JM, Bastiaansen M, Schriefers H. Is beta in agreement with the relatives? Using relative clause sentences to investigate MEG beta power dynamics during sentence comprehension. *Psychophysiology*. 2023:18(10):e14332.

Licklider JCR, Webster JC, Hedlun JM. On the frequency limits of binaural beats. *J Acoust Soc Am*. 1950:22(4):468–473.

Luo Y, Zhang Y, Feng X, Zhou X. Electroencephalogram oscillations differentiate semantic and prosodic processes during sentence reading. *Neuroscience*. 2010:169(2):654–664.

Mallik A, Russo FA. The effects of music & auditory beat stimulation on anxiety: a randomized clinical trial Nisar H, editor. *PLoS One*. 2022:17(3):e0259312.

Marangolo P, Marinelli CV, Bonifazi S, Fiori V, Ceravolo MG, Provinciali L, Tomaiuolo F. Electrical stimulation over the left inferior frontal gyrus (IFG) determines long-term effects in the recovery of speech apraxia in three chronic aphasics. *Behav Brain Res*. 2011:225(2):498–504.

Maris E, Oostenveld R. Nonparametric statistical testing of EEG- and MEG-data. *J Neurosci Methods*. 2007:164(1):177–190.

Meltzer JA, Braun AR. An EEG–MEG dissociation between online syntactic comprehension and post hoc reanalysis. *Front Hum Neurosci*. 2011:4(5):10.

Meyer L. The neural oscillations of speech processing and language comprehension: state of the art and emerging mechanisms. *Eur J Neurosci*. 2018:48(7):2609–2621.

Meyer L, Obleser J, Friederici AD. Left parietal alpha enhancement during working memory-intensive sentence processing. *Cortex*. 2013:49(3):711–721.

Monti A, Ferrucci R, Fumagalli M, Mameli F, Cogiamanian F, Ardolino G, Priori A. Transcranial direct current stimulation (tDCS) and language. *J Neurol Neurosurg Psychiatry*. 2013:84(8):832–842.

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

Oster G. Auditory beats in the brain. *Sci Am*. 1973:229(4):94–103.

Peirce JW. PsychoPy—psychophysics software in python. *J Neurosci Methods*. 2007:162(1–2):8–13.

Penolazzi B, Angrilli A, Job R. Gamma EEG activity induced by semantic violation during sentence reading. *Neurosci Lett*. 2009:465(1): 74–78.

Pérez A, Molinaro N, Mancini S, Barraza P, Carreiras M. Oscillatory dynamics related to the unagreement pattern in Spanish. *Neuropsychologia*. 2012:50(11):2584–2597.

Perez HDO, Dumas G, Lehmann A. Binaural beats through the auditory pathway: from brainstem to connectivity patterns. *Eneuro*. 2020:7(2):ENEURO.0232–ENEU19.2020.

Pion-Tonachini L, Kreutz-Delgado K, Makeig S. ICLabel: an automated electroencephalographic independent component classifier, dataset, and website. *NeuroImage*. 2019:198:181–197.

Pratt H, Starr A, Michalewski HJ, Dimitrijevic A, Bleich N, Mittelman N. A comparison of auditory evoked potentials to acoustic beats and to binaural beats. *Hear Res*. 2010:262(1–2):34–44.

Prystauka Y, Lewis AG. The *power* of neural oscillations to inform sentence comprehension: a linguistic perspective. *Lang Linguist Compass*. 2019:13(9):e12347.

Reedijk SA, Bolders A, Colzato LS, Hommel B. Eliminating the attentional blink through binaural beats: a case for tailored cognitive enhancement. *Front Psychiatry*. 2015:6:82.

Rommers J, Dijkstra T, Bastiaansen M. Context-dependent semantic processing in the human brain: evidence from idiom comprehension. *J Cog Neurosci*. 2013:25(5):762–776.

Ross B, Lopez MD. 40-Hz binaural beats enhance training to mitigate the attentional blink. *Sci Rep*. 2020:10(1):7002.

Schmidt R, Ruiz MH, Kilavik BE, Lundqvist M, Starr PA, Aron AR. Beta oscillations in working memory, executive control of movement and thought, and sensorimotor function. *J Neurosci*. 2019:39(42): 8231–8238.

Schneider JM, Abel AD, Ogiela DA, Middleton AE, Maguire MJ. Developmental differences in beta and theta power during sentence processing. *Dev Cogn Neurosci*. 2016:19:19–30.

Shahin AJ, Picton TW, Miller LM. Brain oscillations during semantic evaluation of speech. *Brain Cogn*. 2009:70(3):259–266.

Vergallito A, Varoli E, Giustolisi B, Cecchetto C, Del Mauro L, Romero Lauro LJ. Mind the stimulation site: enhancing and diminishing sentence comprehension with anodal tDCS. *Brain Lang*. 2020:204:104757.

Wang L, Zhu Z, Bastiaansen M. Integration or predictability? A further specification of the functional role of gamma oscillations in language comprehension. *Front Psychol*. 2012:3:187.

Weiss S, Mueller HM. "Too many *betas* do not spoil the broth": the role of beta brain oscillations in language processing. *Front Psychol*. 2012:3:201.

Weiss S, Mueller H, Schack B, King J, Kutas M, Rappelsberger P. Increased neuronal communication accompanying sentence comprehension. *Int J Psychophysiol*. 2005:57(2):129–141.

Wernick JS, Starr A. Binaural interaction in the superior olivary complex of the cat: an analysis of field potentials evoked by binaural-beat stimuli. *J Neurophysiol*. 1968:31(3): 428–441.

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