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Binaural auditory beats affect long-term memory

Miguel Garcia-Argibay[1] · Miguel A. Santed[2] · José M. Reales[1]

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Abstract

The presentation of two pure tones to each ear separately with a slight difference in their frequency results in the perception of a single tone that fluctuates in amplitude at a frequency that equals the difference of interaural frequencies. This perceptual phenomenon is known as binaural auditory beats, and it is thought to entrain electrocortical activity and enhance cognition functions such as attention and memory. The aim of this study was to determine the effect of binaural auditory beats on long-term memory. Participants ($n = 32$) were kept blind to the goal of the study and performed both the free recall and recognition tasks after being exposed to binaural auditory beats, either in the beta (20 Hz) or theta (5 Hz) frequency bands and white noise as a control condition. Exposure to beta-frequency binaural beats yielded a greater proportion of correctly recalled words and a higher sensitivity index d' in recognition tasks, while theta-frequency binaural-beat presentation lessened the number of correctly remembered words and the sensitivity index. On the other hand, we could not find differences in the conditional probability for recall given recognition between beta and theta frequencies and white noise, suggesting that the observed changes in recognition were due to the recollection component. These findings indicate that the presentation of binaural auditory beats can affect long-term memory both positively and negatively, depending on the frequency used.

Introduction

Binaural auditory beats have aroused the interest of research in psychology, both for their compelling theoretical aspects and their practical implications. The perceptive phenomenon of the binaural beats occurs when two sinusoidal tones with a slightly different frequency are presented separately to the right and left ears, which results in the perception of a single tone of a frequency intermediate between the two presented frequencies that has an amplitude modulation at a frequency that equals the difference between the two (Moore, 2012). For example, exposure to two pure tones of 400 and 410 Hz to each ear, respectively, will produce a perceived frequency of 405 Hz, which oscillates in amplitude with a frequency of 10 Hz. This tone is considered as an illusory tone, because it is the product of the brain processing of two completely different tones (inductive tones). Research has shown that in order for the binaural-beat phenomenon to happen, the difference between the original tones should be between 2 and 35 Hz (Licklider, Webster, & Hedlun, 1950; Perrott & Nelson, 1969). In addition, it has been suggested that the optimum frequency for binaural-beat carrier tones is between 400 and 500 Hz (Oster, 1973; Perrott & Nelson, 1969).

Neurophysiological research has indicated that the binaural auditory beat phenomenon seems to begin in the superior olivary nuclei (Draganova, Ross, Wollbrink, & Pantev, 2008; Oster, 1973; Wernick & Starr, 1968) and the brainstem (Hink, Kodera, Yamada, Kaga, & Suzuki, 1980; Smith, Marsh, & Brown, 1975), manifesting itself also in the reticular formation (Swann, Bosanko, Cohen, Midgley, & Seed,1982) and finally in the cerebral cortex. The studies that have been carried out on binaural beats using EEG measurements have theorized that this phenomenon occurs as a frequency following response (entrainment) of neural networks to the auditory stimulus (Hink et al., 1980; Oster, 1973; Smith et al., 1975). This hypothesis represents the ability of the electrocortical activity of the brain to change the relative power of the different encephalographic ranges already present in the brain to synchronize their neuronal activity at the same frequency as that of the externally presented stimulus (Hink et al., 1980; Huang & Charyton, 2008; Karino, 2006; Karino et al., 2004; Oster, 1973; Smith et al.,

✉ Miguel Garcia-Argibay
miguel.garciaargibay@gmail.com

[1] Department of Behavioral Science, National University of Distance Education (UNED), Juan del Rosal, 10, 28040 Madrid, Spain

[2] Department of Personality Psychology, National University of Distance Education (UNED), Madrid, Spain

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1975; Vernon, 2009). Regardless of the explanation, the possibility that binaural beats may affect the electrocortical activity is of special interest, since it implies the ability to modulate the frequency of the neural oscillations in a passive way and without the need for the previous training.

When the electrical activity of the brain is recorded by electroencephalography (EEG), there is a very wide range of frequencies that vary topologically and temporally. The different band frequencies can be separated by well-known techniques as the Fourier transform and bandpass filters. Nevertheless, what is most relevant in relation with our discussion is that each range of oscillations has been associated with different cognitive functions. For instance, beta waves range in frequency from 12 to 30 Hz (Dickter & Kieffaber, 2013) and appear to be related to certain cognitive processes such as short-term memory (Chen & Huang, 2016; Kopell, Whittington, & Kramer, 2011; Tallon-Baudry, Bertrand, & Fischer, 2001), sentence comprehension (Weiss, Mueller, Schack, King, Kutas, & Rappelsberger, 2005), arousal and vigilance tasks (Lane, Kasian, Owens, & Marsh, 1998), and in verbal learning (Thompson & Obrist, 1964). In addition, low beta activity has also been observed in mental or emotional disorders such as depression and attention deficit hyperactivity disorder (Brenner et al., 1986; Egner & Gruzelier, 2004).

On the other hand, theta frequencies are in the range of 4–7 Hz (Dickter & Kieffaber, 2013) and have been associated with states of relaxation, meditation, drowsiness, and decreased alertness and cognitive performance (Aftanas & Golocheikine, 2002; Hebert & Lehmann, 1977; Jirakittayakorn & Wongsawat, 2017; Lane et al., 1998; Lavallee, Koren, & Persinger, 2011; Paus et al., 1997; Smit, Eling, & Coenen, 2004; Tsai, Jou, Cho, & Lin, 2013; Yamsa-ard & Wongsawat, 2015), as well as an increase in depression scores and lower immediate recall (Wahbeh, Calabrese, Zwickey, & Zajdel, 2007).

The fact that binaural beats can be used to modulate certain electrocortical frequency ranges and that different cognitive processes are related to specific EEG frequency bands has led researchers to believe that they can affect the functioning of both cognitive and emotional processes mentioned above by modifying the relative power in the frequency bands when using binaural beats. Because the frequency bands that can be obtained using binaural beats are between 2 and 35 Hz (Licklider et al., 1950; Perrott & Nelson, 1969), research mainly focused on the study of the cognitive effects that binaural beats have in the alpha, beta, and theta/delta EEG frequency bands, since these include precisely that range. Despite the small number of studies using gamma frequencies, recent studies showed promising results (Colzato, Barone, et al., 2017a; Colzato, Steenbergen, & Sellaro, 2017b; Hommel, Sellaro, Fischer, Borg, & Colzato, 2016).

Our study investigates the effect of binaural beats on the beta and theta band frequencies on long-term memory, in both free recall and recognition. In the first instance, we have tried to confirm the existence of the phenomenon that relates the binaural beats in the beta and theta band with the processes of memory. Second, we have sought to assess if there was a differential involvement of the two processes that underlie the tasks of free recall and recognition: familiarity and recollection (Yonelinas, 2002). For this, on the one hand, we investigated whether the effect is similar across both tasks (free recall and recognition), and on the other hand, we evaluated the effect on the probability of recall given recognition to separate the effect, not on the tasks, but the underlying recollection processes.

Although, as it was stated before, the literature in this area is not very extensive, there has been the previous work on the effect of the binaural beats on memory. Beauchene et al. (2016, 2017) investigated the effect of binaural beats on verbal and visuospatial working memory, concluding that beta-frequency binaural beats increased accuracy in visuospatial working memory tasks and performance in verbal work memory tasks in comparison with the three conditions of control used (without sound, pure tone, and classical music) as with the alpha and theta binaural beats. Ortiz et al. (2008), on the other hand, examined the effects of binaural beats on verbal working memory, before and during the task, for a total of 15 min a day and for 5 days, finding a higher performance when participants were exposed to theta frequencies than to beta frequencies or white noise. Kraus and Porubanová (2015) studied the effect of alpha binaural beats (8–12 Hz) during 12 min of induction on working memory measured by the Automated Operation Span Task (AOSPAN). In this task, the participant must remember the order of a series of items while performing a distracting mathematical task. Subjects showed an improvement in working memory with the alpha binaural-beat exposure compared to the control group, which was exposed to sounds of the sea. It is important to note that all these studies have tried to find the effect of binaural beats on working memory, finding positive effects in certain ranges of frequencies and using as a control condition several different sounds (white noise, pink noise, music, sounds of the sea, etc.) that include a wide range of frequencies. Lane et al. (1998) compared the effect of theta- and beta-frequency binaural-beat stimulation on working memory during a 30-min exposure while the subjects performed vigilance tasks. The investigators found an increase in confusion, fatigue, and difficulties while performing tasks that required concentration when participants were exposed to theta frequencies and an increase in target detection performance and a decrease in the number of false alarms when exposed to beta binaural beats. On the other hand, Wahbeh et al. (2007) measured verbal memory through the Rey Auditory Verbal Learning Test (RAVLT) after exposure to theta binaural beats during a period of 30 min finding a reduction in the number of recalled words compared to the control group, which was exposed to pink noise.

Although these studies have served as a reference for our experimental work, the main difference is that the studies mentioned above tended to focus on the effect of binaural beats on working memory, while we have studied the effects on long-term memory. Thus, we now explore the previous studies on long-term memory. Among the studies that have studied long-term memory, we can cite Kennerly's (1994), who demonstrated that subjects exposed to beta binaural beats during 15 min, before and during the study phase, performed significantly better in both the free recall task and the digit span task, but not in the recognition task in comparison with a control group exposed to instrumental music.

The studies presented thus far provide evidence that there is a relationship between the (supposed) induction of rhythmic brain activities by binaural-beat exposure and various types of memory, both improving and decreasing its performance depending on the frequency used. However, research is scarce in number and depth with results that do not match in all cases. In addition, it is important to differentiate the experimental manipulation used in these studies and its behavioral effects from a possible explanation induced by changes in the relative power of EEG frequency bands aurally manipulated. The first objective is an empirical question, whereas the second is an empirical investigation of the possible causes of the first. It is also important to mention that the majority of the previous studies on the effects of binaural beats on memory either payed particular attention to the retrieval process or did not make a clear separation between encoding and retrieval as sources of the empirically detected effects. This differentiation is key, as a number of studies have postulated encoding and retrieval as different neural substrates (Cabeza et al., 1997; Daselaar, Prince, Dennis, Hayes, Kim, & Cabeza, 2009; de Vanssay-Maigne et al., 2011; Jaiswal, Ray, & Slobounov, 2010; Tulving, Kapur, Craik, Moscovitch, & Houle, 1994).

The present study was performed to deepen the knowledge of the effects that beta and theta binaural beats have on long-term memory, when they are presented during the encoding phase, evaluated by both the free recall and recognition tasks to identify which recovery process is responsible for facilitating or decreasing performance. To the best of our knowledge, this is the first study to investigate the effects of binaural-beat exposure on the encoding phase measured by the free recall and recognition tasks. Furthermore, in addition to investigating the effects of binaural beats on free recall and recognition memory, we wanted to determine which component of recognition was affected. To do so, we calculated the conditional probability for recall given recognition (i.e., the proportion of recalled stimuli among those correctly recognized). According to the dual-process theory (Yonelinas, 2002), retrieval of an item depends on two related but different processes, recollection and familiarity. Results obtained via neuroimaging studies have shown that both processes depend on distinct neural substrates, suggesting that retrieval of information without cues (free recall task) depends on the hippocampus and the prefrontal cortex, whereas retrieval using the same cues as in the study phase (recognition task) depends on familiarity, which is based on the surrounding regions to the hippocampus (Yonelinas, 2002). Familiarity or the type 1 process (recognition) is intuitive, fast, high-capacity, autonomous, and does not require working memory. On the other hand, recollection or the type 2 process (recall) requires working memory. It is slow, limited, and conscious (Evans & Stanovich, 2013). Recollection is a dichotomous process; therefore, a studied stimulus is either recalled or not. However, familiarity is a continuous variable and admits degrees (Mandler, 1980).

In our study, and after reviewing the experimental parameters used in the few previous studies published on this topic, we presented the binaural beats during a 17-min period, since it has been suggested that a long-term exposure (30 min or more) can lead to habituation, thereby decreasing the entrainment possibility (Vernon, Peryer, Louch, & Shaw, 2014) and corresponds to the range of exposure times that has been used in the previous works. Furthermore, we used white noise as the control stimulus because, by definition, its power spectral density is constant and does not depend on frequency. The spectral power density is given by $S_{\mathrm{w}}(f) = \frac{N_o}{2}$, where N_o is the average noise power per unit of bandwidth (W/Hz) between $-W \leqslant f \leqslant W$ (Fernández, 1996). Moreover, by comparing binaural beats against white noise, we are comparing two conditions with active auditory stimulation in which binaural beats supposedly enhances or hinders the performance and white noise acts as a neutral stimulus (Goodin, Ciorciari, Baker, Carrey, Harper, & Kaufman, 2012). Literature review has shown that few studies on this field have also used white noise as a control condition (Dabu-Bondoc et al. 2010; Goodin et al., 2012).

Although the previous studies are scarce, based on them, we can predict that beta-frequency binaural beats will produce greater performance in memorization tasks (free recall and recognition), which in turn will result in a higher proportion of correctly recalled words and a larger sensitivity index d' derived from signal detection theory (SDT), as well as a superior conditional probability for recall given recognition compared to theta binaural beats and white noise exposure. On the other hand, theta-frequency binaural-beat exposure will produce a lower proportion of correctly recalled words, lessened sensitivity measured by d', and a lower conditional probability for recall in contrast to beta-frequency binaural beats and white noise exposure. With our study, we also aim to eliminate the possibility that the induction phase modifies not as much of the storage of information, but the response bias. Therefore, we hypothesized that the response bias *c* from the signal detection theory will not differ from zero in any of the two conditions of the binaural-beat stimulation.

Method

Participants

Thirty-two volunteer participants were selected (23 women and 9 men) from high schools and universities in Pontevedra (Spain). Participants' ages ranged from 14 to 51 years ($M = 22.77$, SD = 10.56). Subjects were randomly assigned to the two experimental conditions; one of them was exposed to beta binaural beats and the other group to theta binaural beats. The groups were balanced in such a way that 16 subjects participated in the beta group ($M = 22.93$ years, SD = 9.54) and other 16 in the theta group ($M = 22.65$ years, SD = 11.81). No significant group differences were observed in terms of age and gender ($p > 0.05$).

All subjects, in addition to undergoing the randomly assigned experimental condition (beta or theta, but not both), were also exposed to white noise, which was used as a control condition. Prior to commencing the study, all participants were informed about the experimental procedure and gave their written informed consent. The experimental protocol was approved by the Ethics Committee of the Universidad Nacional de Educación a Distancia (UNED) and the experiment was conducted in accordance with the Declaration of Helsinki.

Participants indicated that they did not have any hearing or intellectual deficiency were not on pharmacological treatment and did not suffer from disorders such as epilepsy or attention deficit hyperactivity disorder.

Materials

Binaural beats

Binaural-beat audio files were created using Audacity (version 2.1.2; Audacity Team 2015). For the beta group, two sine tones of 390 and 410 Hz were used in the left and right channel, respectively, to produce a 20 Hz binaural beat. For the theta group, two sine tones of 395 and 400 Hz were used to produce a 5 Hz binaural beat. On the other hand, the white noise presented to every participant in the control condition contained all the frequency ranges from 1 to 22,038 Hz. In this way, three experimental conditions were created that we will call beta, theta, and white noise (or control).

For each sound, an amplitude of – 28 dBFS (decibels full scale) and 16-bit audio depth were used. Audio files were saved as uncompressed wav format to avoid frequency loss during the encoding process.

Memory tasks

The experimental procedure was automated using a computer program written in Delphi (visual Pascal). For the creation of the lists of words that were used as stimuli in the study phase, as well as the words that served as the new words in the recognition phase, 80 words of the Spanish language were selected. These were divided into four different lists of 20 words each and were counterbalanced within and between subjects. Words were extracted from a Spanish frequency dictionary (Alameda & Cuetos, 1995) and they had a length ranging between 6 and 8 letters and an average frequency of 136.53 (with a range between 54 and 671).

Procedure

Each subject underwent one of the two conditions: (a) beta binaural beats and white noise or (b) theta binaural beats and white noise. In this way, all participants experienced a single experimental condition (beta or theta) and white noise as a control condition (Fig. 1). Conditions were counterbalanced so that half of participants experienced beta binaural beats first in the condition "a" followed by white noise, while the other half of participants undertook these conditions in reverse order. For the condition "b", half of the participants experienced theta binaural beats prior to white noise exposure, while the other half of the participants experimented these conditions in reverse order.

The study was divided into four different phases for each subject. First, a binaural-beat induction phase was performed for 15 min in one of the three conditions (beta, theta, or white noise), as appropriate, followed by a study phase in which each participant was asked to memorize a list of 20 words during a 2-min period while being exposed to the binaural beats. Consequently, the auditory exposure lasted 17 min in total. In the study phase, each word was displayed on the screen, one at a time, for 2 s and delayed from each other by another 2 s before the next word was shown. Once all the words were presented, the binaural beats ceased and the subject performed a distracting task to avoid primacy and recency effects in which they sorted a series of 10 two-digit numbers from low to high. This task had a variable duration depending on the participant with a range from 3 to 5 min. Next, the tests of free recall and recognition were presented, always in that order. The first test was always a free recall task of the words given in the study phase. Each subject had 2 min to perform this task and type on the computer as many words as he could remember from those previously presented. The following task consisted in the recognition

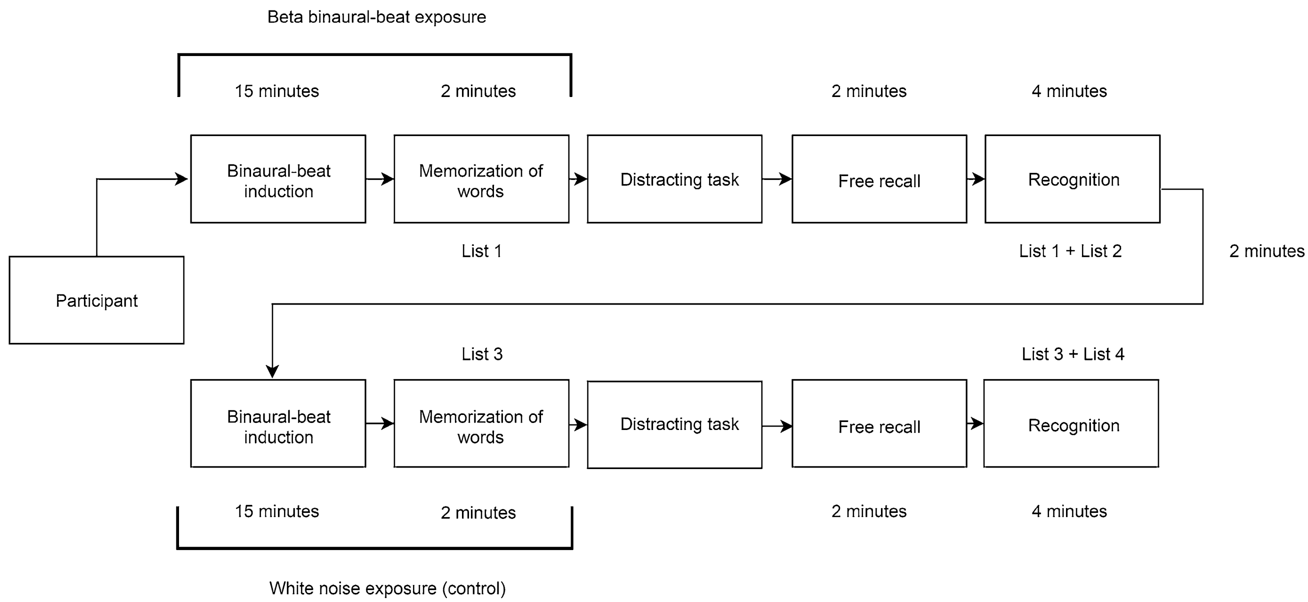

Fig. 1 Flow diagram illustrating the experimental procedure for a subject exposed to beta binaural beats followed by white noise (control condition)

of 40 randomly intermixed words that included the 20 originally given words in the study phase and 20 new words.

The words were presented on the screen, one by one using the same font size that was used in the study phase, and the task of the subjects was to determine if the displayed word was either new or one of those that had previously been memorized (yes/no task) by pressing the old or new buttons below the word. From these results, we obtained the confusion matrix for each subject (hits, misses, false alarms, and correct rejections), and it was analyzed using the signal detection theory obtaining the parametric index d' (sensitivity) and c (response bias). Once the recognition task was completed, the participants had a 2-min rest period. Finally, each participant went on to the next experimental condition, which maintained the same schema: induction phase, study phase, distracting task, free recall, and recognition task. The sequence of the experimental condition (beta and theta) and white noise was counterbalanced in such a way that half of the participants went through the experimental induction (beta or theta) first, followed by the white noise induction and the remaining half did so in the reverse order.

Data analysis

The following dependent variables were measured in the tasks of free recall and recognition. On one hand, free recall was evaluated as the proportion of correctly recalled words. On the other hand, as indicated above, recognition performance was evaluated using the sensitivity index provided by the signal detection theory (Macmillan & Creelman, 2004) as $d' = Z_{\mathrm{Hit}} - Z_{\mathrm{FA}}$, where Z_{H} and Z_{FA} are the standard scores corresponding to the proportion of hits and false alarms, respectively (assuming normality of the distributions of signal and noise), and the response criteria as $c = -\frac{1}{2}\left(Z_{\mathrm{H}} + Z_{\mathrm{FA}}\right)$. Finally, we also calculated the conditional probability for recall given recognition or in other words, the proportion of recalled stimuli among those correctly recognized as $P(\mathrm{Rc/Rn}) = P(\mathrm{Rc} \cap \mathrm{Rn}) \,/\, P(\mathrm{Rn})$, where $P(\mathrm{Rn})$ and $P(\mathrm{Rc})$ are the proportions of correctly recognized and recalled words, respectively. Thus, we considered the correctly recognized words (hits) as the population for a specific condition, and from that population, we computed the proportion of correctly recalled words that pertained to the population.

For each dependent variable (proportion of correctly recalled words, recognition index d' and c, and the conditional probability for recall given recognition) two two-way mixed analysis of variance (ANOVA) and one two-way analysis of covariance (ANCOVA) were conducted. Groups were compared using an ANCOVA including treatment frequency (beta or theta), treatment order, and the interaction between treatment frequency and treatment order as fixed factors and white noise scores as a covariate to control for differences in white noise performance in the two treatment groups. Moreover, we performed two two-way mixed ANOVAs with treatment frequency, treatment order and the interaction between these two variables as fixed factors comparing beta and theta conditions with its corresponding white noise. The level of significance was fixed at $p < 0.05$. All data analyses were performed using SPSS software version 24.0

(IBM SPSS Statistics for Windows, Armonk, NY, USA). The box and whisker plots were generated using R Statistical Software (version 3.4.1; R Foundation for Statistical Computing, Vienna, Austria) applying the Outlier Labeling Rule (Hoaglin, Iglewicz, & Tukey, 1986) utilizing a g value of 2.2 (Hoaglin & Iglewicz, 1987). Being the lower and upper boundary computed, respectively, as $Q1-(2.2\,(Q3-Q1))$ and $Q1+(2.2\,(Q3-Q1))$, where Q_1 is the lower quartile and Q_3 the upper quartile.

Results

Table 1 shows the means and standard deviations for the four dependent variables: proportion of correctly recalled word, sensitivity index d', bias c, and the conditional probability for recall given recognition for the two experimental conditions as well as the scores obtained in the white noise condition for each condition. Note that there are two scores in the white noise condition; each of them belongs to one of the experimental groups (beta condition and theta condition).

Free recall

A two-way ANCOVA was conducted with frequency condition (beta and theta) and treatment order condition as between-subject factors to determine a statistically significant difference between beta and theta conditions in the proportion of correctly recalled words controlling for white noise performance. The results highlighted a significant effect for the condition factor on the proportions of recalled words after controlling for effects of white noise [$F(1,27) = 19.58$, $\mathrm{MSE} = 0.009$, $p < 0.001, \eta_p^2 = 0.420$]. Thus, we can assert that participants recalled a greater number of words when exposed to beta frequencies in comparison with theta frequencies even after controlling for the white noise performance. There was no significant effect of treatment order $\left[F(1,27) = 1.02,\ p = 0.321\right]$ and no significant interaction effect between treatment order and treatment frequency $\left[F(1,27) = 2.55,\ p = 0.122\right]$ rejecting any carryover effect.

To test the hypothesis that the induced binaural frequency type (beta and theta) affected the proportion of correctly recalled words, two two-way mixed ANOVAs were performed with frequency condition (experimental condition and white noise) as a within-subjects factor and treatment order as a between-subject factor. Each ANOVA corresponded to a level of the experimental condition (beta vs. white noise and theta vs. white noise). The results revealed significant differences between beta condition and white noise, pointing out that the number of correctly recalled words in the beta condition was significantly higher than the white noise condition $\left[F(1,14) = 13.05, \mathrm{MSE} = 0.006, p = 0.003, \eta_p^2 = 0.483\right]$ and lower when the theta frequencies were used in comparison with white noise $\left[F(1,14) = 14.44,\ \mathrm{MSE} = 0.003,\ p = 0.002, \eta_p^2 = 0.508\right]$. There was no significant main effect of treatment order in the beta condition $\left[F(1,14) = 0.08,\ p = 0.766\right]$ nor the theta condition $\left[F(1,14) = 0.46,\ p = 0.510\right]$ and no significant interaction effect between treatment order and treatment frequency in the beta condition was found [$F(1,14) = 0.12,\ p = 0.73$], although it was statistically significant in the theta condition $\left[F(1,14) = 6.66,\ p = 0.022\right]$. The simple effect analysis of the interaction showed that the theta and white noise scores did not differ when theta condition was presented first ($p = 0.275$), but they differed significantly when the white noise condition was presented first ($p = 0.007$). When subjects were first exposed to theta binaural beats, it reduced significantly the scores obtained in the free recall task in the white noise condition ($M = 0.39$, SD = 0.079) in comparison with when participants were first exposed to white noise ($M = 0.47$, SD = 0.084). On the other hand, a similar performance was obtained in the theta condition when first exposed to white noise ($M = 0.34$, SD = 0.046) in contrast to when participants first listened to theta binaural beats ($M = 0.36$, SD = 0.064). It seems that the theta exposure affected negatively the performance of the white noise condition when theta binaural beats were presented first, but not in the reverse order.

Table 1 Means (standard deviations) in free recall (proportion of correctly recalled words), recognition (sensitivity d' and bias c), and conditional recall probability given recognition for each condition

Condition	Free recall	Recognition		Conditional probability for recall
	Total	Sensitivity (d')	Bias (c)	Total
Beta	0.46 (0.13)	2.88 (0.42)	0.28 (0.21)	0.53 (0.13)
White noise	0.36 (0.08)	2.14 (0.53)	0.27 (0.22)	0.45 (0.11)
Theta	0.35 (0.10)	2.07 (0.56)	0.30 (0.34)	0.47 (0.17)
White noise	0.43 (0.09)	2.43 (0.76)	0.17 (0.32)	0.50 (0.08)

Recognition

Results from the two-way ANCOVA showed that the condition factor had a significant effect on the sensitivity index $\left[F(1,27) = 32.06,\ \mathrm{MSE} = 0.201,\ p < 0.001, \eta_p^2 = 0.543\right]$ while controlling for white noise exposure. The results expressed that participants exposed to beta binaural beats obtained a higher sensitivity index d' than participants who listened to theta-frequency binaural beats. No significant effect of treatment order $[F(1, 27) = 0.11,\ p = 0.744]$ or interaction between treatment order and treatment frequency was found $[F(1, 27) = 3.92,\ p = 0.061]$.

To determine whether there were significant differences in recognition between the conditions induced by beta and theta binaural beats in the sensitivity index d', two two-way mixed ANOVAs were conducted with frequency condition (experimental condition and white noise) as a within-subjects factor and treatment order as a between-subject factor. Results revealed significant differences between beta and white noise $[F(1, 14) = 23.49, \mathrm{MSE} = 0.187,\ p < 0.001, \eta_p^2 = 0.627]$ and between theta and white noise $\left[F(1, 14) = 5.73,\ \mathrm{MSE} = 0.182,\ p = 0.031, \eta_p^2 = 0.290\right]$. Participants' sensitivity index during the beta exposure was significantly higher than in the white noise condition. On the other hand, participants who listened to theta binaural beats obtained a lower sensitivity index compared to the white noise condition. There was no significant effect of treatment order $[F(1, 14) = 0.34,\ p = 0.568]$ and no significant interaction effect between treatment order and treatment frequency $[F(1, 14) = 0.83,\ p = 0.377]$ in the beta condition nor the theta condition $[F(1, 14) = 0.003,\ p = 0.954;\ F(1, 14) = 3.34,\ p = 0.089]$, respectively.

To evaluate the existence of bias, the same previous analysis was performed on the bias index c scores. The ANCOVA analysis showed no significant difference on the bias index between beta and theta $[F(1, 27) = 1.98, \mathrm{MSE} = 0.050,\ p = 0.171]$ after adjusting for white noise. There was no significant effect of treatment order $[F(1, 27) = 0.61,\ p = 0.442]$ and no significant interaction effect between treatment order and treatment frequency $[F(1, 27) = 0.04,\ p = 0.834]$. The ANCOVA table showed that the intersection of the model was significant $[F(1,\ 27) = 7.24,\ \mathrm{MSE} = 0.05,\ p = 0.01,\ \eta_p^2 = 0.211]$. This means that c scores for both beta [$M = 0.237$, 95% CI (0.121, 0.353)] and theta frequencies [$M = 0.350$, 95% CI (0.235, 0.466)] were significantly different from zero.

Further analysis did not confirm any significant difference between theta and white noise $[F(1, 14) = 4.16, \mathrm{MSE} = 0.038,\ p = 0.061]$, although there is a clear marginally significant trend pointing out the possibility that theta-frequency binaural beats might induce a certain amount of response bias. The results obtained between beta condition and white noise also indicated, more clearly this time, that there were no differences between both frequency conditions $[F(1, 14) = 0.04,\ \mathrm{MSE} = 0.019,\ p = 0.850]$. In this way, we can say that there were no significant differences in bias, although in the theta condition, it was marginally significant indicating a possible trend. No significant main effect of treatment order $[F(1, 14) = 1.21,\ p = 0.290]$ or interaction effect between treatment order and treatment frequency $[F(1, 14) = 0.16\, p = 0.901]$ was found in the beta condition nor the theta condition $[F(1, 14) = 1.19,\ p = 0.294;\ F(1, 14) = 0.05,\ p = 0.833]$ respectively.

Conditional probability

To verify the effect of beta and theta binaural beats on the conditional probability for recall given recognition, a two-way ANCOVA was conducted with frequency (beta and theta) and treatment order as between-subject factors and the score on white noise as a covariate. Results did not reveal any significant differences between beta and theta binaural-beat conditions $[F(1, 27) = 1.52, \mathrm{MSE} = 0.024,\ p = 0.228]$ controlling for white noise. There was no significant effect of treatment order $[F(1, 27) = 0.37,\ p = 0.549]$ and no significant interaction effect between treatment order and treatment frequency $[F(1, 27) = 0.39,\ p = 0.535]$.

The two-way mixed ANOVA failed to reveal differences between beta binaural beats and white noise $[F(1, 14) = 3.33,\ \mathrm{MSE} = 0.010,\ p = 0.089]$, although it was marginally significant. On the other hand, there was no statistically significant difference between theta and white noise $[F(1, 14) = 0.56,\ \mathrm{MSE} = 0.016,\ p = 0.467]$, showing that in both beta and theta conditions, subjects recalled an equivalent number of words to those recalled in the white noise condition, but only when scores were conditioned to the performance in recognition. There was no significant main effect for treatment order, nor was an interaction effect evident between treatment order and treatment frequency in the beta group $[F(1, 14) = 0.03,\ p = 0.870;\ F(1, 14) = 0.01,\ p = 0.91,$ respectively$]$ or the theta group $[F(1, 14) = 0.08,\ p = 0.784;\ F(1, 14) = 1.26,\ p = 0.28,$ respectively$]$. Figure 2 presents the boxplots of the unconditioned proportion of correctly recalled words, d' index, c, and the conditional probability for recall for each group and its corresponding white noise condition.

Discussion

In this article, we have presented a study on the theoretical possibility to entrain the electrocortical activity at certain frequencies to modify free recall and recognition memory. To do this, we performed a study, where we have presented binaural beats during the encoding phase in the beta and theta band frequencies, keeping all other factors identical between the two conditions to evaluate the effect that this induction had on memory. Based on the previous studies, we hypothesized that beta binaural-beat exposure would produce an increase in long-term memory measured by an

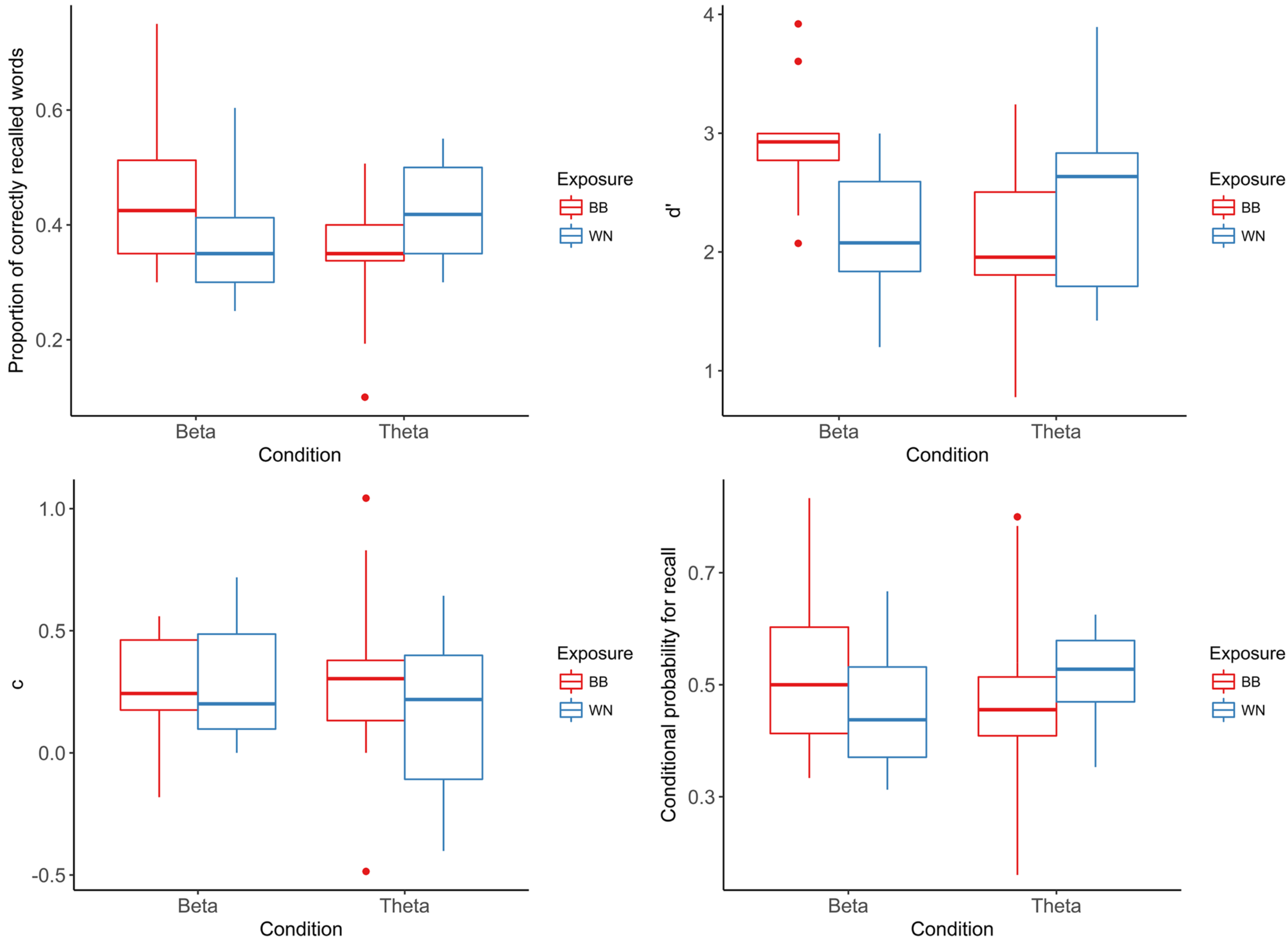

Fig. 2 Boxplot of the different dependent variables for each condition. Outliers are illustrated by circles. *BB* binaural-beat exposure, *WN* white noise exposure

increment in the proportion of recalled words, the sensitivity index d' in recognition memory, and the proportion of recalled words conditioned to those recognized. As a control condition, we used white noise, because it has a constant power spectral density and does not depend on frequency.

The results of this study showed evidence that binaural-beat exposure for a period of 17 min affects the performance on free recall and recognition tasks, which in turn suggests that such exposure times do not produce a habituation effect to binaural beats. The observed effects were partially consistent with our predictions, so that beta-frequency binaural beats were associated with a higher proportion of correctly recalled words in a free recall task and a higher sensitivity index d' in recognition in comparison with theta-frequency binaural beats and white noise. This increase in the sensitivity index d' indicated a lower degree of overlap between the studied words and the non-studied word distributions. Our results are consistent with those obtained by Kennerly (1994) in long-term memory and Lane et al. (1998) in vigilance tasks, corroborating the hypothesis that binaural beats enhance cognition (Colzato et al. 2017a, 2017b; Reedijk, Bolders, & Hommel, 2013; Reedijk, Bolders, Colzato, & Hommel, 2015). Moreover, despite the fact that participants' bias did not differ between the beta and white noise condition, it was positive for both binaural-beat frequencies, showing that they affected the criterion positively.

On the other hand, when subjects listened to theta binaural beats, we observed a lower proportion of correctly recalled words and a smaller sensitivity index d' in comparison with participants exposed to beta binaural beats and white noise. These results suggest that theta binaural beats produced a cognitive performance impairment in free recall and recognition memory. This impairment may be tentatively explained by theta frequencies which appear to be positively related to psychological states incompatible with the encoding of the information, such as relaxation, decreasing anxiety and activation levels, increase of meditation depth and hypnotic susceptibility (Aftanas & Golocheikine, 2001; Brady & Stevens, 2000; Jirakittayakorn & Wongsawat, 2017; Lane et al., 1998; Lavallee et al., 2011; Le Scouarnec et al., 2001; Padmanabhan et al. 2005; Wahbeh et al., 2007), and other types of cognitive functions such as selective attention, motor control, spatial processing, and visual memory (Başar-Eroglu, Başar, Demiralp, & Schürmann, 1992; Baumeister, Reinecke, Liesen, & Weiss, 2008; Bösel, 1993; Buzsáki, 2006; Grunwald et al., 1999; Pennekamp, Bösel, Mecklinger, & Ott, 1994). Although EEG theta band frequencies have their usefulness in other tasks, they seem to hinder the memory encoding process of the information, leading to a worse performance in recall and recognition tasks. Moreover, theta power seems to be larger throughout retrieval than during encoding (Klimesch, Doppelmayr, Schimke, & Ripper, 1997; Klimesch, Schimke, & Schwaiger, 1994). Other studies have suggested that this decrease on long-term memory could be due to a decrease in the systems of vigilance and regulation (Saletu & Grünberger, 1985). Regarding the bias, our results showed that participants exposed to theta binaural beats used a more conservative criterion that biased the subject toward responding "new" (non-studied).

Our study seems to point to a greater specification of the factor responsible for the effect of binaural beats on memory. In particular, the experimental results obtained in relation with the conditioned recall compared to the results of the non-conditioned recall seem to indicate that the positive effects obtained on memory by beta binaural beats and the negative effects of theta binaural beats are due to the recollection component of memory and not the familiarity component. The dual-process theory points out that while recognition can be achieved either by the familiarity component or through the recollection of information, recall relies exclusively on conscious retrieval. Consequently, having conditioned in the last analysis the recall scores to a successful recognition, we expected to estimate the recollection component in recall. The fact that in doing so, the differences found in the beta condition have been eliminated (albeit marginally significant) seem to indicate that the positive effect in this condition may be mainly due to the recollection component of recognition, as the effect was restricted to the recollection measure. Conversely, the decrease in performance in the theta condition when we conditioned the execution to the successful recognition was clearly nil (not marginally significant as in the previous case). This fact seems to suggest that the observed decrease in free recall may also be due mainly to the recollection component.

The above explanation affects the procedural aspects that may be involved in the retrieval of information and its differential involvement by beta and theta binaural beats. On the other hand, we can hypothesize that the observed effects may be due to a modulation of the brain activity by binaural beats (Beauchene et al., 2016, 2017; Brady & Stevens, 2000; Gao et al., 2014; Ioannou et al. 2015; Karino, 2006; Karino et al., 2004). We can rule out the possibility that the differences observed between binaural auditory beats exposure and white noise are due to differences in motivation or fatigue due to the fact that the participants obtained higher scores in the beta condition in the different tasks regardless of whether the binaural beat or white noise had been presented first. Future studies should determine if our results could be replicated using white noise exposure as a between-subject factor to avoid potential interferences. This result further supports the hypothesis that beta binaural-beat exposure enhances long-term memory despite order of presentation. However, the present study lacks EEG measures to confirm that, as suggested in the literature, the presentation of beta- and theta-frequency binaural auditory beats might have induced the brain to synchronize their electroencephalographic waves in these bands frequencies (neural entrainment). There are other possible explanations for our results; for instance, it might be plausible that the observed increase in performance on memory is due not so much to the increase of the relative power in the beta band, but a reduction of the relative power in the theta band during beta binaural-beat exposure (Gao et al., 2014) and thereby reducing fatigue and improving mood (Lane et al., 1998; Wahbeh et al., 2007). Another feasible interpretation might be that the effects found in the memory tasks after binaural-beat exposure could be mediated by the influence of emotional arousal on memory, as it has been extensively reported (Anderson, Wais, & Gabrieli, 2006; Buchanan & Lovallo, 2001; Eysenck, 1976; Knight & Mather, 2009; Nashiro & Mather, 2011; Nielson & Bryant, 2005; Nielson & Powless, 2007; Smeets et al. 2008; Strange, Hurlemann, & Dolan, 2003). This capability of the emotional arousal to modulate memory implies both the retrieval and encoding processes of memory, but also the perception and attention to the stimulus (LaBar & Phelps, 1998). To further our research and answer these questions, we plan to continue this research to include EEG and electrophysiological measures (electrodermal activity to evaluate arousal state) as well as resolving some problems that may limit this study. Among these limitations, we must mention that we have only used visual stimuli and the age range of the participants has been very wide. Another limitation of this study is the gender disparity of the sample, being 71.87% women. This difference is a variable to be taken into account in future research, as the previous work showed that there is a difference in the perception of binaural beats depending on gender, with men perceiving them at a higher frequency band than women (Tobias, 1965).

Surprisingly, the proportion of correctly recalled words in the white noise condition was lower only when theta-frequency binaural beats were presented first, displaying a carryover effect. The observed carryover effect might have distorted the results obtained during the white noise exposure and therefore, these results need to be interpreted with caution. Notwithstanding that a carryover effect was observed in the free recall task when participants were exposed first to theta-frequency binaural beats, this effect allowed us to highlight a noteworthy and unanswered question regarding how long the psychophysiological effects of the binaural-beat exposure remain after the cessation of this exposure. Although carryover effects are undesirable, in this study it helped to reveal the existence of a relatively long washout period. The 26-min (i.e., 9 min to complete the free recall, recognition, and distracting tasks, a 2-min break, and a 15-min induction) washout period between frequency interventions was inadequate to impede a carryover effect when participants were exposed to theta-frequency binaural beats. This unexpected finding could be due to the drowsiness and relaxation caused by theta binaural-beat exposure, suggesting that these effects were maintained over time even during white noise exposure. Therefore, we can hypothesize that the inhibitory effects after theta exposure were maintained for a longer period of time compared to beta binaural beats. This finding should be considered in future research to avoid a potential carryover effect. Finally, the fact that the carryover effect was only present in the free recall task and not in the recognition task might suggest, as our results from the conditional probability for recall indicated, the implication of the recollection component, being selectively influenced by binaural beats. This could denote a difference between recollection and familiarity in terms of the areas involved during binaural-beat exposure. Based on the previous research, which established the engagement of different brain regions in recollection and familiarity, we can theorize a possible influence in the hippocampus and the parahippocampal cortex (Davachi, Mitchell, & Wagner, 2003; Kensinger & Schacter, 2006; Ranganath et al., 2004) caused by binaural-beat exposure that affected the recollection component.

So far, binaural-beat research has fundamentally focused on its effects during the retrieval phase, but not much is known about its effect during the encoding phase. Further experimental work is needed to estimate the differences in the results in memory tasks when participants are exposed to binaural beats during both the encoding and retrieval of the information to determine the extent to which both phases contribute to an improvement in memory. Another possible line of research could be to determine if shorter binaural-beat induction periods elicit the same improvements in memory tasks such as those found in other studies in which it is possible to observe changes in the EEG using a short exposure of 1000 ms (Karino et al., 2004). Furthermore, it would be interesting to ascertain the possible influence of theta binaural beats in cognitive flexibility, since the previous studies have suggested that reduced frontal theta activity may be correlated with a lower cognitive flexibility (Sauseng et al., 2006; Yeung, Han, Sze, & Chan, 2016). In addition, on a wider level, it could be examined if this increase in the number of recalled words also occurs in participants with ADHD or elderly people who have difficulties memorizing and remembering information, which opens new appealing lines of research in clinical areas.

In summary, behavioral effects of binaural-beat induction are a relatively under-researched area, which may have important practical applications as long as replicable empirical evidence is provided and assertions by unsupported data are not made. Nevertheless, we believe that a fundamental issue for future research would be to replicate the obtained effects and investigate the psychophysiological mechanisms underlying those cases in which binaural beats show effectiveness to affect the cognitive performance (memory and attention). Hence, further research is needed to understand what behavioral, cognitive, and physiological changes occur and in which clinical areas they can be applied with efficiency and cost effectiveness.

Conclusions

Based on our results, we can conclude that beta-frequency binaural beats, in comparison with theta-frequency binaural beats and white noise, are an effective method to enhance the long-term memory, being improved in both free recall and recognition. Specifically, beta binaural beats seem to improve the encoding of new information in an entirely passive way without any previous active training, making binaural beats a useful tool, interesting, and worthy of further in-depth research.

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Compliance with ethical standards

Conflict of interest Miguel Garcia-Argibay, Miguel A. Santed, and José M. Reales declare having no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

Aftanas, L. I., & Golocheikine, S. A. (2001). Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: High-resolution EEG investigation of meditation. *Neuroscience Letters, 310*(1), 57–60. https://doi.org/10.1016/S0304-3940(01)02094-8.

Aftanas, L. I., & Golocheikine, S. A. (2002). Non-linear dynamic complexity of the human EEG during meditation. *Neuroscience Letters, 330*(2), 143–146. https://doi.org/10.1016/S0304-3940(02)00745-0.

Alameda, J. R., & Cuetos, F. (1995). *Diccionario de frecuencias de las unidades lingüísticas del español*. Servicio de Publicaciones de La Universidad de Oviedo.

Anderson, A. K., Wais, P. E., & Gabrieli, J. D. E. (2006). Emotion enhances remembrance of neutral events past. *Proceedings of the National Academy of Sciences, 103*(5), 1599–1604. https://doi.org/10.1073/pnas.0506308103.

Audacity Team. (2015). Audacity®: Free Audio Editor and Recorder.

Başar-Eroglu, C., Başar, E., Demiralp, T., & Schürmann, M. (1992). P300-response: Possible psychophysiological correlates in delta and theta frequency channels. A review. *International Journal of Psychophysiology, 13*(2), 161–179. https://doi.org/10.1016/0167-8760(92)90055-G.

Baumeister, J., Reinecke, K., Liesen, H., & Weiss, M. (2008). Cortical activity of skilled performance in a complex sports related motor task. *European Journal of Applied Physiology, 104*(4), 625–631. https://doi.org/10.1007/s00421-008-0811-x.

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), e0166630. https://doi.org/10.1371/journal.pone.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), 26014. https://doi.org/10.1088/1741-2552/aa5d67.

Bösel, R. (1993). Die cerebrale Theta-Rhythmizität unterstützt kontextabhängige Diskriminationsleistungen. *Kognitionswissenschaft, 3*(1), 53–69.

Brady, B., & Stevens, L. (2000). Binaural-beat induced theta EEG activity and hypnotic susceptibility. *American Journal of Clinical Hypnosis, 43*(1), 53–69. https://doi.org/10.1080/00029157.2000.10404255.

Brenner, R. P., Ulrich, R. F., Spiker, D. G., Sclabassi, R. J., Reynolds, C. F., Marin, R. S., & Boller, F. (1986). Computerized EEG spectral analysis in elderly normal, demented and depressed subjects. *Electroencephalography and Clinical Neurophysiology, 64*(6), 483–492. https://doi.org/10.1016/0013-4694(86)90184-7.

Buchanan, T. W., & Lovallo, W. R. (2001). Enhanced memory for emotional material following stress-level cortisol treatment in humans. *Psychoneuroendocrinology, 26*(3), 307–317. https://doi.org/10.1016/S0306-4530(00)00058-5.

Buzsáki, G. (2006). *Rhythms of the brain*. New York: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195301069.001.0001.

Cabeza, R., Grady, C. L., Nyberg, L., McIntosh, A. R., Tulving, E., Kapur, S., Craik, F. I. M. (1997). Age-related differences in neural activity during memory encoding and retrieval: A positron emission tomography study. *The Journal of Neuroscience, 17*(1), 391–400.

Chen, Y., & Huang, X. (2016). Modulation of alpha and beta oscillations during an n-back task with varying temporal memory load. *Frontiers in Psychology*, 6, 20–31. https://doi.org/10.3389/fpsyg.2015.02031.

Colzato, L. S., Barone, H., Sellaro, R., & Hommel, B. (2017a). 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.

Colzato, L. S., Steenbergen, L., & Sellaro, R. (2017b). The effect of gamma-enhancing binaural beats on the control of feature bindings. *Experimental Brain Research, 235*(7), 2125–2131. https://doi.org/10.1007/s00221-017-4957-9.

Dabu-Bondoc, S., Vadivelu, N., Benson, J., Perret, D., & Kain, Z. N. (2010). Hemispheric synchronized sounds and perioperative analgesic requirements. *Anesthesia & Analgesia, 110*(1), 208–210. https://doi.org/10.1213/ANE.0b013e3181bea424.

Daselaar, S. M., Prince, S. E., Dennis, N. A., Hayes, S. M., Kim, H., & Cabeza, R. (2009). Posterior midline and ventral parietal activity is associated with retrieval success and encoding failure. *Frontiers in Human Neuroscience, 3*, 13. https://doi.org/10.3389/neuro.09.013.2009.

Davachi, L., Mitchell, J. P., & Wagner, A. D. (2003). Multiple routes to memory: Distinct medial temporal lobe processes build item and source memories. *Proceedings of the National Academy of Sciences, 100*(4), 2157–2162. https://doi.org/10.1073/pnas.0337195100.

de Vanssay-Maigne, A., Noulhiane, M., Devauchelle, A. D., Rodrigo, S., Baudoin-Chial, S., Meder, J. F., Chassoux, F. (2011). Modulation of encoding and retrieval by recollection and familiarity: Mapping the medial temporal lobe networks. *NeuroImage, 58*(4), 1131–1138. https://doi.org/10.1016/j.neuroimage.2011.06.086.

Dickter, C. L., & Kieffaber, P. D. (2013). *EEG methods for the psychological sciences*. London: Sage.

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.

Egner, T., & Gruzelier, J. H. (2004). EEG biofeedback of low beta band components: Frequency-specific effects on variables of attention and event-related brain potentials. *Clinical Neurophysiology, 115*(1), 131–139. https://doi.org/10.1016/S1388-2457(03)00353-5.

Evans, J. S. B. T., & Stanovich, K. E. (2013). Dual-process theories of higher cognition. *Perspectives on Psychological Science, 8*(3), 223–241. https://doi.org/10.1177/1745691612460685.

Eysenck, M. W. (1976). Arousal, learning, and memory. *Psychological Bulletin, 83*(3), 389–404. https://doi.org/10.1037/0033-2909.83.3.389.

Fernández, M. M. (1996). Señales aleatorias y ruido. *ETS de Ingenieros de Telecomunicación*. http://lmi.bwh.harvard.edu/papers/pdfs/1996/martin-fernandezCOURSE96b.pdf.

Gao, X., Cao, H., Ming, D., Qi, H., Wang, X., Wang, X., Zhou, P. (2014). Analysis of EEG activity in response to binaural beats with different frequencies. *International Journal of Psychophysiology, 94*(3), 399–406. https://doi.org/10.1016/j.ijpsycho.2014.10.010.

Goodin, P., Ciorciari, J., Baker, K., Carrey, A.-M., Harper, M., & Kaufman, J. (2012). A high-density EEG investigation into steady state binaural beat stimulation. *PLoS One, 7*(4), e34789. https://doi.org/10.1371/journal.pone.0034789.

Grunwald, M., Weiss, T., Krause, W., Beyer, L., Rost, R., Gutberlet, I., & Gertz, H.-J. (1999). Power of theta waves in the EEG of human subjects increases during recall of haptic information. *Neuroscience Letters, 260*(3), 189–192. https://doi.org/10.1016/S0304-3940(98)00990-2.

Hebert, R., & Lehmann, D. (1977). Theta bursts: An EEG pattern in normal subjects practising the transcendental meditation technique. *Electroencephalography and Clinical Neurophysiology, 42*(3), 397–405. https://doi.org/10.1016/0013-4694(77)90176-6.

Hink, R. F., Kodera, K., Yamada, O., Kaga, K., & Suzuki, J. (1980). Binaural interaction of a beating frequency-following response. *International Journal of Audiology, 19*(1), 36–43. https://doi.org/10.3109/00206098009072647.

Hoaglin, D. C., & Iglewicz, B. (1987). Fine-tuning some resistant rules for outlier labeling. *Journal of the American Statistical Association, 82*(400), 1147. https://doi.org/10.2307/2289392.

Hoaglin, D. C., Iglewicz, B., & Tukey, J. W. (1986). Performance of some resistant rules for outlier labeling. *Journal of the American Statistical Association, 81*(396), 991. https://doi.org/10.2307/2289073.

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, 7*, 1287. https://doi.org/10.3389/fpsyg.2016.01287.

Huang, T. L., & Charyton, C. (2008). A comprehensive review of the psychological effects of brainwave entrainment. *Alternative Therapies in Health and Medicine, 14*(5), 38–50.

Ioannou, C. I., Pereda, E., Lindsen, J. P., & Bhattacharya, J. (2015). Electrical brain responses to an auditory illusion and the impact of musical expertise. *PLoS One, 10*(6), e0129486. https://doi.org/10.1371/journal.pone.0129486.

Jaiswal, N., Ray, W., & Slobounov, S. (2010). Encoding of visual–spatial information in working memory requires more cerebral efforts than retrieval: Evidence from an EEG and virtual reality study. *Brain Research, 1347*, 80–89. https://doi.org/10.1016/j.brainres.2010.05.086.

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.

Karino, S. (2006). Neuromagnetic responses to binaural beat in human cerebral cortex. *Journal of Neurophysiology, 96*(4), 1927–1938. https://doi.org/10.1152/jn.00859.2005.

Karino, S., Yumoto, M., Itoh, K., Uno, A., Matsuda, M., Yamakawa, K., Kaga, K. (2004). Magnetoencephalographic study of human auditory steady-state responses to binaural beat. *International Congress Series, 1270*, 169–172. https://doi.org/10.1016/j.ics.2004.05.072.

Kennerly, R. C. (1994). *An empirical investigation into the effect of beta frequency binaural beat audio signals on four measures of human memory* (*MSc thesis*). West Georgia College.

Kensinger, E. A., & Schacter, D. L. (2006). Amygdala activity is associated with the successful encoding of item, but not source, information for positive and negative stimuli. *Journal of Neuroscience, 26*(9), 2564–2570. https://doi.org/10.1523/JNEUROSCI.5241-05.2006.

Knight, M., & Mather, M. (2009). Reconciling findings of emotion-induced memory enhancement and impairment of preceding items. *Emotion, 9*(6), 763–781. https://doi.org/10.1037/a0017281.

Kopell, N., Whittington, M. A., & Kramer, M. A. (2011). Neuronal assembly dynamics in the beta1 frequency range permits short-term memory. *Proceedings of the National Academy of Sciences, 108*(9), 3779–3784. https://doi.org/10.1073/pnas.1019676108.

Kraus, J., & Porubanová, M. (2015). The effect of binaural beats on working memory capacity. *Studia Psychologica, 57*(2), 135–145. https://doi.org/10.21909/sp.2015.02.689.

LaBar, K. S., & Phelps, E. A. (1998). Arousal-mediated memory consolidation: Role of the medial temporal lobe in humans. *Psychological Science, 9*(6), 490–493. https://doi.org/10.1111/1467-9280.00090.

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

Lavallee, C. F., Koren, S. A., & Persinger, M. A. (2011). A quantitative electroencephalographic study of meditation and binaural beat entrainment. *The Journal of Alternative and Complementary Medicine, 17*(4), 351–355. https://doi.org/10.1089/acm.2009.0691.

Le Scouarnec, R. P., Poirier, R. M., Owens, J. E., Gauthier, J., Taylor, A. G., & Foresman, P. A. (2001). Use of binaural beat tapes for treatment of anxiety: A pilot study of tape preference and outcomes. *Alternative Therapies in Health and Medicine, 7*(1), 58–63.

Licklider, J. C. R., Webster, J. C., & Hedlun, J. M. (1950). On the frequency limits of binaural beats. *The Journal of the Acoustical Society of America, 22*(4), 468–473. https://doi.org/10.1121/1.1906629.

Macmillan, N. A., & Creelman, C. D. (2004). *Detection theory: A user's guide*. Mahwah: Psychology Press.

Mandler, G. (1980). Recognizing: The judgment of previous occurrence. *Psychological Review, 87*(3), 252–271. https://doi.org/10.1037/0033-295X.87.3.252.

Moore, B. C. J. (2012). *An introduction to the psychology of hearing* (6th edn.). London: Brill.

Nashiro, K., & Mather, M. (2011). Effects of emotional arousal on memory binding in normal aging and Alzheimer's disease. *The American Journal of Psychology, 124*(3), 301–312. https://doi.org/10.5406/amerjpsyc.124.3.0301.

Nielson, K. A., & Bryant, T. (2005). The effects of non-contingent extrinsic and intrinsic rewards on memory consolidation. *Neurobiology of Learning and Memory, 84*(1), 42–48. https://doi.org/10.1016/j.nlm.2005.03.004.

Nielson, K. A., & Powless, M. (2007). Positive and negative sources of emotional arousal enhance long-term word-list retention when induced as long as 30 min after learning. *Neurobiology of Learning and Memory, 88*(1), 40–47. https://doi.org/10.1016/j.nlm.2007.03.005.

Ortiz, T., Martínez, A. M., Fernández, A., Maestu, F., Campo, P., Hornero, R., 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.

Padmanabhan, R., Hildreth, A. J., & Laws, D. (2005). A prospective, randomised, controlled study examining binaural beat audio and pre-operative anxiety in patients undergoing general anaesthesia for day case surgery. *Anaesthesia, 60*(9), 874–877. https://doi.org/10.1111/j.1365-2044.2005.04287.x.

Paus, T., Zatorre, R. J., Hofle, N., Caramanos, Z., Gotman, J., Petrides, M., & Evans, A. C. (1997). Time-related changes in neural systems underlying attention and arousal during the performance of an auditory vigilance task. *Journal of Cognitive Neuroscience, 9*(3), 392–408. https://doi.org/10.1162/jocn.1997.9.3.392.

Pennekamp, P., Bösel, R., Mecklinger, A., & Ott, H. (1994). Differences in EEG-theta for responded and omitted targets in a sustained attention task. *Journal of Psychophysiology, 8*(2), 131–141.

Perrott, D. R., & Nelson, M. A. (1969). Limits for the detection of binaural beats. *The Journal of the Acoustical Society of America, 46*(6B), 1477–1481. https://doi.org/10.1121/1.1911890.

Ranganath, C., Yonelinas, A. P., Cohen, M. X., Dy, C. J., Tom, S. M., & D'Esposito, M. (2004). Dissociable correlates of recollection and familiarity within the medial temporal lobes. *Neuropsychologia, 42*(1), 2–13. https://doi.org/10.1016/j.neuropsychologia.2003.07.006.

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, 6*, 82. https://doi.org/10.3389/fpsyt.2015.00082.

Reedijk, S. A., Bolders, A., & Hommel, B. (2013). The impact of binaural beats on creativity. *Frontiers in Human Neuroscience, 7*(November), 786. https://doi.org/10.3389/fnhum.2013.00786.

Saletu, B., & Grünberger, J. (1985). Memory dysfunction and vigilance: Neurophysiological and psychopharmacological aspects.

Annals of the New York Academy of Sciences, 444(1 Memory Dysfun), 406–427. https://doi.org/10.1111/j.1749-6632.1985.tb37604.x.

Smeets, T., Otgaar, H., Candel, I., & Wolf, O. T. (2008). True or false? Memory is differentially affected by stress-induced cortisol elevations and sympathetic activity at consolidation and retrieval. *Psychoneuroendocrinology, 33*(10), 1378–1386. https://doi.org/10.1016/j.psyneuen.2008.07.009.

Smit, A. S., Eling, P. A. T., & Coenen, A. M. (2004). Mental effort affects vigilance enduringly: After-effects in EEG and behavior. *International Journal of Psychophysiology, 53*(3), 239–243. https://doi.org/10.1016/j.ijpsycho.2004.04.005.

Smith, J. C., Marsh, J. T., & Brown, W. S. (1975). Far-field recorded frequency-following responses: Evidence for the locus of brainstem sources. *Electroencephalography and Clinical Neurophysiology, 39*(5), 465–472. https://doi.org/10.1016/0013-4694(75)90047-4.

Strange, B. A., Hurlemann, R., & Dolan, R. J. (2003). An emotion-induced retrograde amnesia in humans is amygdala- and -adrenergic-dependent. *Proceedings of the National Academy of Sciences, 100*(23), 13626–13631. https://doi.org/10.1073/pnas.1635116100.

Swann, R., Bosanko, S., Cohen, R., Midgley, R., & Seed, K. M. (1982). *The brain—a user's manual*. New York: GP Putnam's Sons, p. 92.

Tallon-Baudry, C., Bertrand, O., & Fischer, C. (2001). Oscillatory synchrony between human extrastriate areas during visual short-term memory maintenance. *The Journal of Neuroscience, 21*(20), RC177. Retrieved from http://www.jneurosci.org/content/21/20/RC177.

Thompson, L. W., & Obrist, W. D. (1964). EEG correlates of verbal learning and overlearning. *Electroencephalography and Clinical Neurophysiology, 16*(4), 332–342. https://doi.org/10.1016/0013-4694(64)90067-7.

Tobias, J. V. (1965). Consistency of sex differences in binaural-beat perception. *International Audiology, 4*(2), 179–182. https://doi.org/10.3109/05384916509074132.

Tsai, J.-F., Jou, S.-H., Cho, W., & Lin, C.-M. (2013). Electroencephalography when meditation advances: A case-based time-series analysis. *Cognitive Processing, 14*(4), 371–376. https://doi.org/10.1007/s10339-013-0563-3.

Tulving, E., Kapur, S., Craik, F. I., Moscovitch, M., & Houle, S. (1994). Hemispheric encoding/retrieval asymmetry in episodic memory: Positron emission tomography findings. *Proceedings of the National Academy of Sciences, 91*(6), 2016–2020.

Vernon, D. (2009). *Human potential: Exploring techniques used to enhance human performance*. New York: Routledge.

Vernon, D., Peryer, G., Louch, J., & Shaw, M. (2014). Tracking EEG changes in response to alpha and beta binaural beats. *International Journal of Psychophysiology, 93*(1), 134–139. https://doi.org/10.1016/j.ijpsycho.2012.10.008.

Wahbeh, H., Calabrese, C., Zwickey, H., & Zajdel, D. (2007). Binaural beat technology in humans: A pilot study to assess neuropsychologic, physiologic, and electroencephalographic effects. *The Journal of Alternative and Complementary Medicine, 13*(2), 199–206. https://doi.org/10.1089/acm.2006.6201.

Weiss, S., Mueller, H. M., Schack, B., King, J. W., 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.

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.

Yamsa-ard, T., & Wongsawat, Y. (2015). The observation of theta wave modulation on brain training by 5 Hz-binaural beat stimulation in seven days. *Engineering in Medicine and Biology Society (EMBC), 2015–Novem*, 6667–6670. https://doi.org/10.1109/EMBC.2015.7319922.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*(3), 441–517. https://doi.org/10.1006/jmla.2002.2864.