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ORIGINAL ARTICLE

Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: a meta-analysis

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Abstract

Binaural auditory beats are a perceptual phenomenon that occurs when presenting separately to each ear two tones that slightly differ in their frequency. It has been suggested that binaural beats can influence cognition and mental states among others. The objective of this meta-analysis was to study the effect of binaural beats on memory, attention, anxiety, and analgesia. Twenty-two studies met our inclusion criteria for this meta-analysis. The results, based on 35 effect sizes, showed an overall medium, significant, consistent effect size ($g = 0.45$). Meta-regression results indicated that it does not seem to be necessary to mask binaural beats with white noise or pink noise in terms of effectiveness, obtaining similar effects with unmasked binaural beats. Moreover, the findings suggest that binaural-beat exposure before, and before and during the task produces superior results than exposure during the task. Time under exposure contributed significantly to the model indicating that longer periods are advisable to ensure maximum effectiveness. Our meta-analysis adds to the growing evidence that binaural-beat exposure is an effective way to affect cognition over and above reducing anxiety levels and the perception of pain without prior training, and that the direction and the magnitude of the effect depends upon the frequency used, time under exposure, and the moment in which the exposure takes place.

Introduction

The presentation of two pure sinusoidal tones to each ear separately with a steady intensity, but with a slight difference in their frequency results in the perception of a single illusionary tone with a frequency equal to the mean frequency of the two tones and an amplitude that fluctuates with a frequency that equals to the difference between the two tones (Oster, 1973). For example, a two-tone exposure of 400 and 410 Hz to each ear separately will be perceived as a single tone with a frequency of 405 Hz that varies in amplitude with a frequency of 10 Hz (Moore, 2012). The information presented to each ear separately is processed and combined in a way that is perceived as a single unified percept by a phenomenon known as binaural integration (Lentz et al., 2014).

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Previous research studies have indicated that binaural auditory beats initially originate in the superior olivary nuclei (Draganova, Ross, Wollbrink, & Pantev, 2008; Oster, 1973) and the brainstem (Hink, Kodera, Yamada, Kaga, & Suzuki, 1980; Smith, Marsh, & Brown, 1975), then moves to the reticular formation (Swann, Bosanko, Cohen, Midgley, & Seed, 1982) where it can subsequently be measured in the cerebral cortex as a frequency following response (FFR) through electroencephalographic (EEG) measurements (Hink et al., 1980; Oster, 1973; Smith et al., 1975). The term FFR refers to the tendency of the electrocortical activity of the brain to change the relative power and synchronize its neuronal activity to the same frequency as an externally presented stimulus (Huang & Charyton, 2008; Vernon, 2009). Several lines of evidence suggest that it occurs by a phase-reset and entrainment (phase-lock) of neuronal excitability to the binaural beats, which produce changes in response gain and amplify neuronal responses that in turn causes the rhythmic fluctuations in neuronal excitability to be aligned in such a way that the high excitability phases will be prone to coincide with the events of the stimulus (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008; Schroeder & Lakatos, 2009).

Recent research appears to validate the view that binaural beats are capable of altering functional connectivity between regions of the brain (Gao et al., 2014; Karino, 2006; Karino et al., 2004) as well as the connectivity of cortical networks (Beauchene, Abaid, Moran, Diana, & Leonessa, 2016; Beauchene, Abaid, Moran, Diana, & Leonessa, 2017; Ioannou, Pereda, Lindsen, & Bhattacharya, 2015). However, other researchers failed to find evidence of neural entrainment, challenging this assumption by suggesting that the increase in interhemispheric coherence between the auditory cortices, which express the synchrony between the neural oscillations of both hemispheres, is a form of the auditory system to solve a challenging binaural perception by increasing the communication between the two auditory cortices (Solcà, Mottaz, & Guggisberg, 2016).

Although there is no agreement upon the mechanism underlying binaural auditory beats (entrainment vs. interhemispheric coherence), there is growing support for the claim that binaural auditory beats affect cognition and psychophysiological states. Numerous studies have reported that binaural-beat exposure leads to psychophysiological changes. For instance, theta/delta-band frequencies have been used successfully to reduce anxiety levels (Isik, Esen, Büyükerkmen, Kilinç, & Menziletoglu, 2017; Le Scouarnec et al., 2001; McConnell, Froeliger, Garland, Ives, & Sforzo, 2014; Padmanabhan, Hildreth, & Laws, 2005; Wahbeh, Calabrese, Zwickey, & Zajdel, 2007b; Weiland et al., 2011), and to increase hypnotic susceptibility (Brady & Stevens, 2000) and creativity (Reedijk, Bolders, & Hommel, 2013). Along similar lines, binaural beats have also been associated with improvements in attention and vigilance tasks (Colzato, Barone, Sellaro, & Hommel, 2017a; Hommel, Sellaro, Fischer, Borg, & Colzato, 2016; Lane, Kasian, Owens, & Marsh, 1998; Reedijk, Bolders, Colzato, & Hommel, 2015), long- and short-term memory (Beauchene et al., 2016; Beauchene et al., 2017; Colzato, Steenbergen, & Sellaro, 2017b; Garcia-Argibay, Santed, & Reales, 2017; Kennerly, 1994; Kraus & Porubanová, 2015; Ortiz et al., 2008; Wahbeh, Calabrese, & Zwickey, 2007a), and perceived pain (Dabu-Bondoc, Vadivelu, Benson, Perret, & Kain, 2010; Ecsy, Jones, & Brown, 2017; Zampi, 2016). However, other researchers have not been able to confirm the effectiveness of binaural beats in some of these areas (e.g., attention). For example, Kennel, Taylor, Lyon, and Bourguignon (2010) found that exposure to binaural beats did not reduce inattention symptoms in children diagnosed with attention-deficit disorder and hyperactivity. In the same vein of non-congruent results, Crespo, Recuer, Galvez, and Begoña (2013) failed to detect any improvement in attention measurements using a perceptual test of differences in a two-group design—experimental and control. These findings seem to indicate that the results between studies are somewhat inconsistent and/or that some experimental variables are moderating the results (e.g., cognitive function assessed, time under exposure, frequency used, type of sound employed to mask the binaural beat, or moment of exposure).

One can see a variety of scientific reports regarding binaural beats where some researchers found positive effects with binaural-beat exposure in certain cognitive functions, while others did not seem to find any effect in that same functions. Therefore, the aim of this meta-analysis was to evaluate the degree and direction to which memory, attention, anxiety levels, and analgesia requirements are affected by binaural-beat exposure with an eye to finding any pattern about the implied mechanisms, and the true expectations that can be achieved by the use of this technique. Furthermore, we explored the possible moderation effect upon binaural-beat efficacy of time under exposure, moment of exposure, and the type of sound used to mask the binaural beat.

Methods

Literature search and selection criteria

We performed a systematic search on PubMed (Medline), IEEE, and ScienceDirect databases to identify relevant studies on the subject. The search was limited to English language papers, using the keywords ”binaural beat”, ”binaural beats” or ”binaural auditory beats” and were searched in these databases up to October 2017. The flowchart of the meta-analysis is displayed in Fig. 1.

Two authors (M. Garcia-Argibay and J. M. Reales) independently reviewed the retrieved studies, rating results were compared, and where differences were noted, they were discussed and reconciled. The methodology, design, features, and results of each study were described and coded by the first author.

To be included in the meta-analysis, studies had to fulfill four criteria: (1) use of binaural auditory beats as treatment or experimental manipulated factor; (2) experimental studies; (3) application of binaural beats in practical areas and where the number of studies in each area is at least three; and (4) the studies provided sufficient information to extract effect sizes (ES) from descriptive or inferential statistics.

The literature search yielded 68 studies of which 43 were excluded since the studies did not meet the inclusion criteria for the meta-analysis. Three additional studies could not be included as the reported data were insufficient for the calculation of effect sizes. This resulted in a total of 22 studies (k = 35 ESs) that were included in the present analysis.

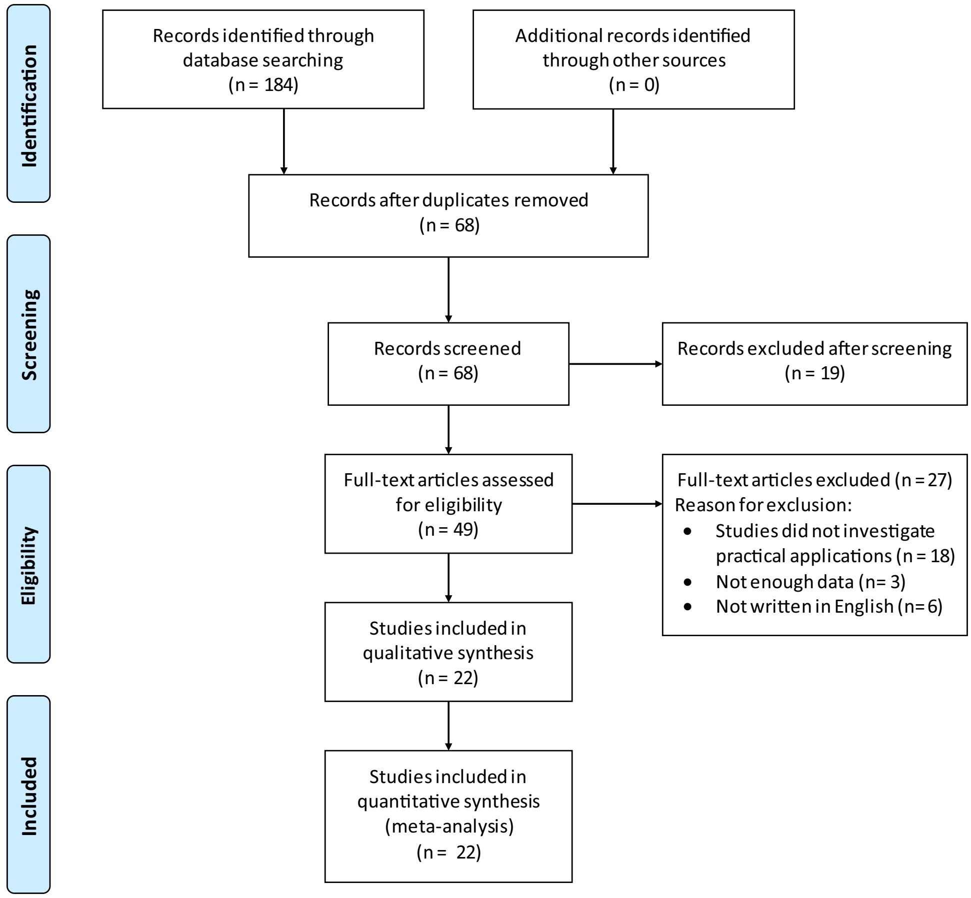

Fig. 1 Flowchart of literature search in the meta-analysis

Data extraction

The following information was extracted from the studies that met the inclusion criteria: surname of the first author, year of publication, study design, type of participant, binaural-beat frequency used, time under exposure, moment of exposure, comparison group, type of sound used to mask the binaural beat (if any), number of participants in each condition, and outcome measurement.

Effect size calculation

Cohen's d effect sizes (Hedges & Olkin, 1985) were calculated using the following equation:

$$d = \frac{M_t - M_c}{\mathrm{SD}_{\mathrm{pooled}}},$$

where M_t is the mean of the experimental condition, M_c is the mean of the control condition, and $\mathrm{SD}_{\mathrm{pooled}}$ is the pooled standard deviation of the two groups, experimental and control. When means and standard deviations were not reported in the original study, effect sizes were calculated using F, t, r or p values (Rosenthal, 1994) using the following equations as suitable:

$$d = \frac{2\sqrt{F}}{\sqrt{df}} = \frac{2t_{\mathrm{indep}}}{\sqrt{df}} = \frac{t_{\mathrm{dep}}}{\sqrt{df}}.$$

Effect sizes from p values (independent t test) were calculated using the *compute.es* package in *R*. On the other hand, Hedges' unbiased estimate g was calculated using the following equations as appropriate:

$$g = \frac{d}{\sqrt{\frac{N}{df}}} = \frac{r}{\sqrt{1-r^2}}\sqrt{\frac{N-1}{N}}.$$

Table 1 summarizes the first author's surname, year of publication, sample sizes, Hedges' g, and sampling variance of the effect size for the included studies in the meta-analysis.

Quality assessment

Before including the studies for meta-analysis, a quality assessment was conducted for each potentially relevant trial. This quality assessment was composed of eight items,

Table 1 Surname, year of publication, grouping variable, sample size of the groups, ES, and sampling variance of the effect size

ID	Study	Subgroup	n_t	n_c	g	Variance
1	Beauchene et al. (2017) β	Memory	34	34	0.138	0.06
2	Beauchene et al. (2017) θ	Memory	34	34	0.188	0.06
3	Beauchene et al. (2017) α	Memory	34	34	0.12	0.06
4	Beauchene et al. (2016) β	Memory	28	28	0.14	0.07
5	Beauchene et al. (2016) θ	Memory	28	28	− 0.31	0.07
6	Beauchene et al. (2016) α	Memory	28	28	− 0.28	0.07
7	Colzato et al. (2017a)	Attention	18	18	0.694	0.12
8	Colzato et al. (2017b)	Memory	20	20	1.098	0.12
9	Crespo et al. (2013)	Attention	20	20	0.274	0.10
10	Dabu-Bondoc et al. (2010)	Analgesia	20	20	0.676	0.11
11	Hommel et al. (2016)	Attention	20	20	0.666	0.11
12	Isik et al. (2017)	Anxiety	30	30	0.725	0.07
13	Garcia-Argibay et al. (2017) β	Memory	16	16	0.907	0.14
14	Garcia-Argibay et al. (2017) θ	Memory	16	16	− 0.819	0.14
15	Garcia-Argibay et al. (2017) β	Memory	16	16	1.501	0.16
16	Garcia-Argibay et al. (2017) θ	Memory	16	16	− 0.526	0.13
17	Kennel et al. (2010)	Attention	10	10	0.511	0.21
18	Kennerly (1994)	Memory	27	23	0.709	0.09
19	Kennerly (1994)	Memory	27	23	0.492	0.08
20	Kennerly (1994)	Memory	27	23	0.679	0.09
21	Kliempt et al. (1999)	Analgesia	25	26	1.634	0.11
22	Kraus and Porubanová (2015)	Memory	20	20	0.681	0.11
23	Lane et al. (1998)	Memory	29	29	0.326	0.07
24	Lane et al. (1998)	Memory	29	29	0.424	0.07
25	Lewis et al. (2004)	Analgesia	15	15	0.895	0.15
26	McConnel et al. (2014)	Anxiety	10	11	0.47	0.19
27	Ortiz et al. (2008) θ	Memory	18	18	0.626	0.12
28	Ortiz et al. (2008) β	Memory	18	18	− 0.323	0.11
29	Padmanabhan et al. (2005)	Anxiety	35	35	0.712	0.06
30	Reedijk et al. (2015) γ	Attention	24	24	0.827	0.09
31	Reedijk et al. (2015) α	Attention	24	24	0.426	0.08
32	Solcà et al. (2016)	Attention	18	18	0.689	0.12
33	Wahbeh et al. (2007a)	Memory	4	4	− 1.217	0.59
34	Wahbeh et al. (2007b)	Anxiety	8	8	0.786	0.27
35	Wahbeh et al. (2007b)	Anxiety	8	8	0.666	0.26

ES Hedges' effect size, n_t experimental group, n_c control group, α alpha, β beta, θ theta, γ gamma

and they were based on methodological questions regarding randomization, double-blinding, sample size, existence of a control group and baseline measurements, dropouts, and use of validated assessment instruments (Botella & Meca, 2015).

Each item of the quality score answered with "*yes*" received one point, whereas when answered "*no*" a zero was received. The criterion for determining the adequacy of the sample size was established based upon the median of the studies; studies with a sample size smaller than the median (31) were considered to be of low quality. All points were summed, with the maximum score being 8. Thereafter, a simple linear regression was performed to determine the degree of influence on the absolute values of the effect sizes by the quality of the included studies. Results failed to show evidence of influence on effect size based on the quality of the included studies, $b = 0.06$, $t(33) = 0.98$, $p = .335$, $R^2 = .028$, which was corroborated by the Bayes factor, $BF_{10} = 0.471$, $r_{\text{scale}} = \sqrt{2}/4$, compared to the null model (intercept only) assuming a non-informative prior distribution. Although effect size is a measure that is not affected by sample size, we also assessed if this specific criterion of study quality was able to predict differences in effect sizes. Our results showed that sample size was not a significant predictor of effect sizes, $b = 0.003$, $t(33) = 0.85$, $p = .399$, $R^2 = .022$, $BF_{10} = 0.431$.

Data analysis

The estimated effect size g (Hedges, 1981) and its variance were computed for each study. Heterogeneity was assessed across studies for each outcome by the Cochran's Q test with a chi-square distribution with k–1 degrees of freedom, where k was the number of studies; the I^2 statistic, which measures the percentage of total variation between study effects (Borenstein, Hedges, Higgins, & Rothstein, 2009; Higgins, 2003); and a Galbraith plot (Galbraith, 1988). A random-effects model with restricted maximum likelihood estimation (REML) was employed, as it cannot be assumed that the treatment effect of the selected studies are identical in the population (Borenstein, Hedges, Higgins, & Rothstein, 2010) due to the fact that different periods of binaural-beat exposure, frequencies, and carrier tones have been used. REML estimations were used as they are more adequate since they do not underestimate the variances (Thompson & Sharp, 1999). For the random-effects model, effect sizes were weighted by the inverse variance, summing the within- and between-study variance $w_i = (v_i + \tau^2)^{-1}$, where τ^2 is the between-study variance and v_i is the within-study variance. Additionally, subgroup analyses were performed to reduce the heterogeneity among studies. Thus, effect sizes were grouped according to the outcome (i.e., memory, attention, anxiety, and analgesia) based on a random-effects model with REML estimation.

Furthermore, a weighted, multiple linear mixed-effects regression analysis was undertaken using the inverse of the variance as the weight variable to determine the impact of relevant factors on the absolute values of the effect sizes. The regression has been weighted so that studies with lower variance have more influence in the analysis. Analysis of multicollinearity was assessed between all our predictor variables and effect sizes using variance inflation factor (VIF) to avoid the inclusion of highly correlated predictor variables. Multicollinearity was determined as VIF and tolerance values greater than 10 and less than 0.1, respectively (O'brien, 2007). Homoscedasticity and normality of regression residuals were assessed utilizing the Breusch–Pagan test (Breusch and Pagan, 1979) and a visual inspection of a normal quantile–quantile (Q–Q) plot, respectively.

The possible influence of publication bias was evaluated with a series of analyses: a funnel plot using the standard error (SE) of effect sizes (Peters, Sutton, Jones, Abrams, & Rushton, 2008; Sterne & Egger, 2001), a funnel plot with trim-and-fill method (Duval & Tweedie, 2000), the Egger regression asymmetry test (Egger, Smith, Schneider, & Minder, 1997), the adjusted rank correlation (Begg & Mazumdar, 1994), and the normal Q–Q plot (Wang & Bushman, 1998). Additionally, to analyze the possibility of p-hacking, a p-curve analysis was performed (Simonsohn, Simmons, & Nelson, 2015). The p-curve analysis was performed using the p-curve web application 4.06 (Simonsohn et al., 2015). p-curve analysis was complemented with a p-uniform analysis as it includes adjusted publication bias estimates. The p-uniform analysis was computed using the *puniform* package (van Aert, Wicherts, & van Assen, 2016). All statistical analyses were performed with R 3.4.1 (R Core Team, 2017) using the *metafor* package (Viechtbauer & Cheung, 2010).

Study descriptions

Twenty-two studies met inclusion criteria for meta-analysis, and the characteristics of the selected ones are summarized in Table 2. The total number of participants ranged from 4 to 35 in both the experimental ($M = 20.41$, SD = 8.18) and the control groups ($M = 20.32$, SD = 8.04), and the total time under binaural-beat exposure lasted between 4 and 130 min ($M = 26$, SD = 27.83).

Nine original studies researched the effects of binaural beats on memory. Beauchene et al. (2016, 2017) measured verbal and visuospatial working memory in the dual n-back task. Their results indicated that only beta-frequency binaural beats increased performance in both visuospatial and verbal working memory tasks compared to three control conditions—no sound, a constant tone, and classical music—as well as to theta and alpha binaural-beat conditions. Colzato et al. (2017b) studied the effect of a 10-min exposure to gamma-frequency binaural beats produced in the top-down control of feature bindings compared to the control group, wherein participants listened to a constant tone of 340 Hz. Results indicated that gamma binaural-beat exposure enhanced visual feature binding, but not visuomotor binding and thus improved selectivity in updating episodic memory traces. Kennerly (1994) investigated the effect of beta binaural-beat exposure for 45 min on the number of correctly recalled words in the recognition and free recall tasks and the performance in a digit-span task. The results showed that beta exposure increased the number of recalled words in the free recall task and the performance in the digit-span task compared to the control group that was exposed to instrumental music, but no differences were found in the recognition task. Kraus and Porubanová (2015) found significant improvement in working memory capacity when participants were exposed to alpha-frequency binaural beats for 12 min while they performed the automated OSPAN task, in which subjects have to remember the order of a series of items while performing mathematical distracting tasks. Lane et al. (1998) compared the performance between the beta and theta conditions in a recognition task observing that beta-frequency binaural beat exposure produced a greater number of correct targets as well as a smaller number of false alarms, whereas participants exposed to theta-frequency binaural beats displayed a larger number of

Table 2 Study design, participants, frequency used, grouping, exposure time (min), number of subjects, outcome, selected group comparison, masking and moment of exposure of the included studies

Study	Study design	Participants	Grouping	Exposure	Frequency	*N*	Outcome	Comparison group	BB masking	Moment of exposure
Beauchene et al. (2017)	COC	Healthy adults	Memory	5	Beta	34	Visuospatial memory	Blank tape	Pure	During
Beauchene et al. (2017)	COC	Healthy adults	Memory	5	Theta	34	Visuospatial memory	Blank tape	Pure	During
Beauchene et al. (2017)	COC	Healthy adults	Memory	5	Alpha	34	Visuospatial memory	Blank tape	Pure	During
Beauchene et al. (2016)	COC	Healthy adults	Memory	5	Beta	28	Verbal working memory	Blank tape	Pure	During
Beauchene et al. (2016)	COC	Healthy adults	Memory	5	Theta	28	Verbal working memory	Blank tape	Pure	During
Beauchene et al. (2016)	COC	Healthy adults	Memory	5	Alpha	28	Verbal working memory	Blank tape	Pure	During
Colzato et al. (2017a)	RCT	Healthy adults	Attention	3	Gamma	36	Attention task	Constant tone	WN	Before and during
Colzato et al. (2017b)	RCT	Healthy adults	Memory	10	Gamma	40	Visual working memory	Constant tone	WN	Before and during
Crespo et al. (2013)	RCT	Healthy adults	Attention	20	Beta	60	Attention task	Music	Music	Before
Dabu-Bondoc et al. (2010)	RCT	Surgery patients	Analgesia	30	Complex	60	Amount of anesthesia	WN	Music	Before and during
Garcia-Argibay et al. (2017)	RCT	Healthy adults	Memory	17	Beta	32	Free recall task	WN	Pure	Before and during
Garcia-Argibay et al. (2017)	RCT	Healthy adults	Memory	17	Theta	32	Recognition task	WN	Pure	Before and during
Garcia-Argibay et al. (2017)	RCT	Healthy adults	Memory	17	Beta	32	Free recall task	WN	Pure	Before and during
Garcia-Argibay et al. (2017)	RCT	Healthy adults	Memory	17	Theta	32	Recognition task	WN	Pure	Before and during
Hommel et al. (2016)	RCT	Healthy adults	Attention	40	Gamma	40	Attention task	WN	WN	Before and during
Isik et al. (2017)	RCT	Healthy adults	Anxiety	10	Theta	60	Anxiety levels	Blank tape	Pure	Before
Kennel et al. (2010)	RCT	ADHD children	Attention	20	Beta	20	Attention task	Music	Music	During
Kennerly (1994)	RCT	Healthy adults	Memory	45	Beta	50	Free recall task	Music	Music	Before and during
Kennerly (1994)	RCT	Healthy adults	Memory	45	Beta	50	Recognition task	Music	Music	Before and during
Kennerly (1994)	RCT	Healthy adults	Memory	45	Beta	50	Digit-span task	Music	Music	Before and during
Kliempt et al. (1999)	RCT	Surgery patients	Analgesia	63	Complex	76	Amount of anesthesia	Blank tape	Pure	Before and during
Kraus and Porubanová (2015)	RCT	Healthy adults	Memory	12	Alpha	20	Working memory	Sea sounds	Pink noise	Before
Lane et al. (1998)	COC	Healthy adults	Memory	30	Beta	29	Recognition task (hit)	Theta BB	Pink noise	During
Lane et al. (1998)	COC	Healthy adults	Memory	30	Beta	29	Recognition task (FA)	Theta BB	Pink noise	During
Lewis et al. (2004)	RCT	Healthy adults	Analgesia	130	NR	30	Amount of anesthesia	Blank tape	Pink noise	During
McConnel et al. (2014)	RCT	Healthy adults	Anxiety	20	Theta	21	Heart rate variability	Pink noise	Pink noise	Before
Ortiz et al. (2008)	COC	Healthy adults	Memory	15	Theta	18	Verbal working memory	Baseline	Pure	During
Ortiz et al. (2008)	COC	Healthy adults	Memory	15	Beta	18	Verbal working memory	Baseline	Pure	During
Padmanabhan et al. (2005)	RCT	Surgery patients	Anxiety	30	NR	70	Anxiety levels	Blank tape	Music	Before
Reedijk et al. (2015)	COC	Healthy adults	Attention	3	Gamma	24	Attention task	Baseline	WN	Before and during
Reedijk et al. (2015)	COC	Healthy adults	Attention	3	Alpha	24	Attention task	Baseline	WN	Before and during
Solcà et al. (2016)	RCT	Healthy adults	Attention	4	Alpha	18	Dichotic digit task	Baseline	Pure	During
Wahbeh et al. (2007a)	COC	Healthy adults	Memory	30	Theta	4	Verbal working memory	Blank tape	Pink noise	During
Wahbeh et al. (2007b)	UCT	Healthy adults	Anxiety	30	Delta	8	Quality of life	Baseline	Pink noise	Before
Wahbeh et al. (2007b)	UCT	Healthy adults	Anxiety	30	Delta	8	Anxiety levels	Baseline	Pink noise	Before

COC crossover controlled trial, *RCT* randomized controlled trial, *UCT* uncontrolled trial, *NR* not reported, *WN* white noise, *BB* binaural beat, *FA* false alarms false alarms. Ortiz et al. (2008) explored the effect of beta and theta binaural-beat exposure for 15 min per day and for 5 days in a verbal working memory task. The researchers concluded that, contrary to the aforementioned studies, theta-frequency exposure resulted in a greater number of recalled words compared to the white noise and beta-frequency exposure condition. Wahbeh et al. (2007a) exposed participants to theta-band frequencies while they completed the Rey Auditory Verbal List Test (RAVLT) obtaining a significant reduction in the number of recalled words compared to the control group. Garcia-Argibay et al. (2017) demonstrated that beta-frequency exposure during the encoding phase for 17 min increased both the number of correctly recalled words in the free recall task and the sensitivity index (d') in a recognition task. On the contrary, theta binaural-beat exposure reduced the number of correctly remembered words and the sensitivity index in free recall and recognition tasks, respectively, in comparison to when participants were exposed to white noise.

Six original studies researched the effect of binaural beats on attention. Colzato et al. (2017a) observed that gamma-frequency binaural beat exposure produced a smaller global-precedence effect when compared to the control condition that the authors attributed to an increased attentional focus. Hommel et al. (2016) demonstrated that cognitive control can be influenced toward flexibility by listening to gamma-frequency binaural beats. This in turn displays that gamma-frequency binaural beats positively affect the ability to shift with flexibility between strategies and tasks to achieve an appropriate solution for a given problem. Reedijk et al. (2015) highlighted that gamma binaural beats enhanced attentional control eliminating the attentional blink in comparison to both alpha binaural beat and constant tone conditions. This effect occurs when two successive target stimuli embedded in a stream are presented quickly one after the other. When the second target is presented close in time to the first one, the former is often not reported caused by a competition for attentional resources. Additionally, the authors pointed out that individual differences in spontaneous eye-blink rates determined the effectiveness of gamma binaural-beat exposure, eliminating the attentional blink only in individuals with low spontaneous eye-blink rates. In contrast, Solcá et al. (2016) could not find significant differences between monaural and binaural-beat exposure (beta and theta) on the dichotic digit task, both exhibiting enhancing effects when compared to the baseline. Crespo et al. (2013) and Kennel et al. (2010), on the other hand, could not find any significant improvement on attention evaluated by a perception test of differences and the performance in the Children's Color Trails Test 1, respectively, while subjects were exposed to beta- and theta-frequency binaural beats.

Three studies were found wherein the analgesic effect of binaural beats was assessed. Dabu-Bondoc et al. (2010) and Kliempt, Ruta, Ogston, Landeck, & Martay (1999) measured the amount of anesthesia used on patients who listened to complex binaural beats (Hemi-sync) that contained multi-layered frequencies (i.e., alpha, beta, theta, delta, and gamma). Results confirmed a considerable smaller analgesia requirement when subjects were exposed to binaural beats compared to the control group that was not exposed to any auditory stimulus. Similarly, Lewis, Osborn, & Roth (2004) also obtained a reduction in the amount of anesthesia needed when patients were exposed to theta-frequency binaural beats in a laparoscopic bariatric surgery compared to the control group, which listened to a blank tape.

Four studies explored the effectiveness of the binaural beats on anxiety levels. Padmanabhan et al. (2005) and Wahbeh et al. (2007b) studied the effect of theta-frequency binaural beats on anxiety measured by the State–Trait Anxiety Inventory (STAI) obtaining a significant reduction in anxiety scores compared to the control group, as well as an increase in quality of life scores. McConnell et al. (2014), on the other hand, measured the heart rate variability when participants were exposed to theta-frequency binaural beats, producing statistically significant differences in the sympathetic and parasympathetic activities compared to the control group, which in turn, indicated a greater self-reported relaxation. Isik et al. (2017) demonstrated very recently that a short exposure of 10 min to theta-frequency binaural beats produced a significant reduction of anxiety levels prior to a dental operation measured by the Visual Analogue Scale (VAS) compared to the control group that listened to a blank tape.

Results

Prior to performing the meta-analysis, the data were evaluated for influential studies. As shown in Fig. 2, the difference in fit standardized (DFFITS; Belsley, Kuh, & Welsch, 1980), the ratio of generalized variances (COVRATIO; Viechtbauer & Cheung 2010), and the Cook's distance (Cook & Weisberg, 1982) analyses identified study number 21 (Kliempt et al., 1999) as a possible outlier/influential study since it stands out significantly from the rest, whereas the hat values did not suggest so. In no case did we observe a Cook's distance or DFFITS greater than 1; all cases were below 0.2. The results from the leave-one-out sensitivity analysis displayed insignificant influences on the overall effect size and heterogeneity. The overall random-effects model presented an effect size of $g = 0.446$ 95% CI [.28, .62], $z = 5.11$, $\tau^2 = .16$, $I^2 = 61.34\%$, and after removing study 21, shifted to 0.41, 95% CI [.25, .57], $z = 5.04$, $\tau^2 = .12$, $I^2 = 54.98\%$. Therefore, we decided to include all studies in the follow-up analysis. A comparison of the effect sizes between the different groups can be seen in Fig. 3.

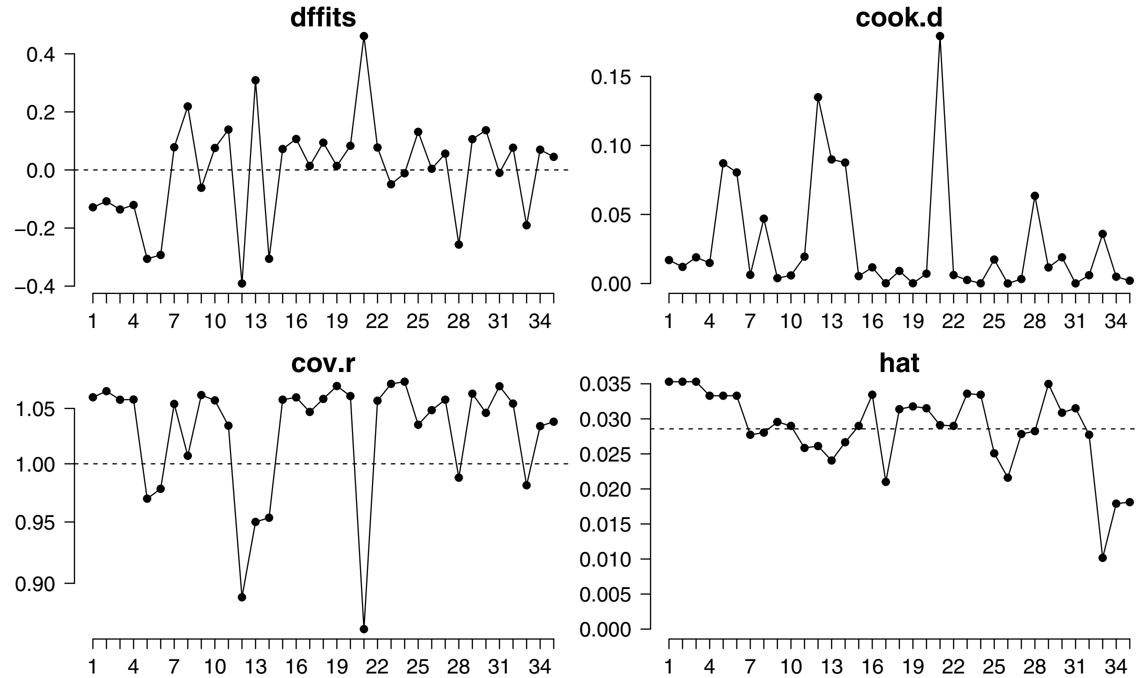

Fig. 2 Plot of four outlier diagnostic statistics for every study; *DFFITS* difference in standardized fits, *cook.d* cook's distance, *cov.r* ratio of generalized variances, *hat* leverages or hat values

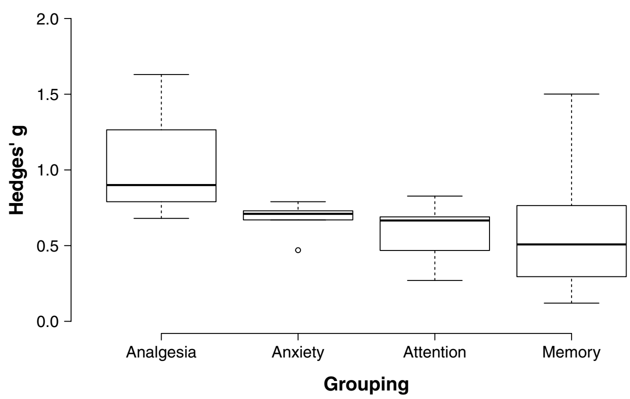

Fig. 3 Comparison of the effect sizes between the different groups

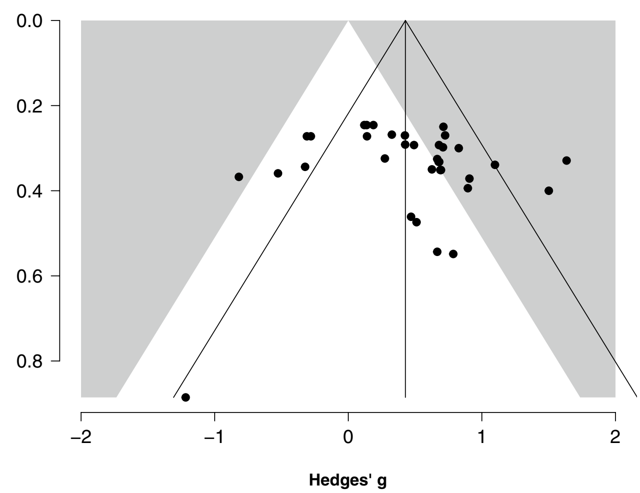

Fig. 4 Funnel plot with pseudo-95% CI of the estimated effect sizes and its standard error in individual studies for the overall studies

Publication bias

Due to the fact that we included in our analysis only published studies, there is a risk of publication bias, since studies that could not find statistically significant results may not be published and, therefore, added to the meta-analysis. The Egger regression test did not reveal any significant publication bias ($z = -0.019$ $p = .984$), although, as shown in Fig. 4, the funnel plot displayed a slight asymmetry to the left. The trim-and-fill analysis suggested that no studies were missing. This lack of publication bias was also supported by the Begg–Mazumdar rank correlation test, which did not reach significance ($\tau^2 = .12$, $p = .298$). Finally, the roughly linear shape of the normal Q–Q plot showed a symmetric distribution of the data, suggesting that nonsignificant studies have not been deleted and that the residual heterogeneity in the effect sizes was normally distributed (see Fig. 5). After verifying that no significant bias effect was present in the data, a subgroup analysis was performed (i.e., memory, attention, analgesia, and anxiety).

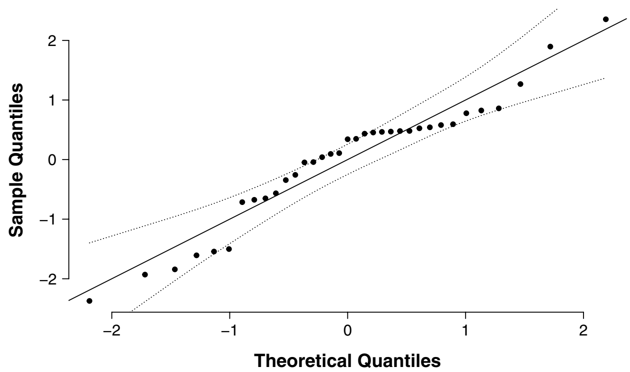

Fig. 5 Normal quantile plot for the effect sizes plotted against the quantiles of the standard normal distribution. Dotted lines represent the 95% upper and lower CIs

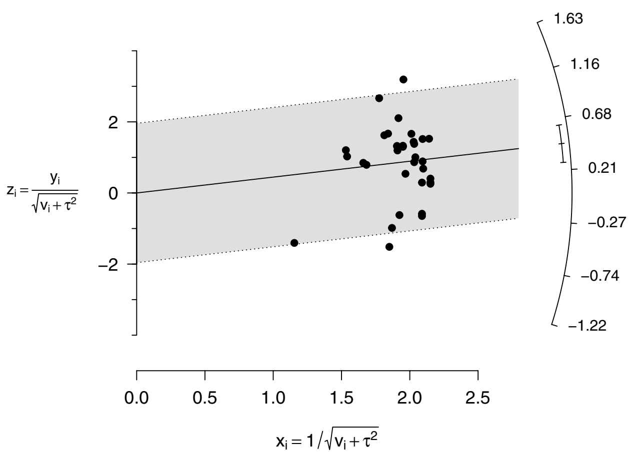

Fig. 6 Galbraith radial plot with 95% CIs of the effects of binaural beats across studies. v_i variance, y_i Hedges' g, τ_2 between-study estimated variance

Homogeneity

The test for heterogeneity of the included studies revealed evidence of a moderate amount of heterogeneity, $Q(34) = 86.30$, $p < .001$, $I^2 = 61.34\%$, 95% CI [42.53%, 80.39%], $\tau^2 = .16$, AIC = 59.41, and log-likelihood = – 27.71. The Galbraith plot provided complementary evidence of heterogeneity, displaying that two studies, number 21 and 33, fell outside the 95% CI (see Fig. 6). Consequently, a random-effects model was performed stratified by subgroups due to the degree of heterogeneity measured by Q and I^2 (Ades, Lu, & Higgins, 2005). The amount of heterogeneity accounted for by the different subgroups was 33.98%, $Q(31) = 63.79$, $p < .001$, $I^2 = 51.07\%$, 95% CI [27.61%, 77.31%], $\tau^2 = .10$, AIC = 55.24, and log-likelihood = -22.62. Both models were compared using a likelihood ratio test (LRT). The LRT displayed a significant difference between the two models, $\chi^2(3) = 10.16$, $p = .017$, representing the latter a better fit for the data. Figure 7 summarizes the results from the subgroup analyses in a forest plot. As can be seen, most of the variability (69%) comes from the memory subgroup, $Q(19) = 56.61$, $p < .001$, in which 6 effect sizes revealed a hindering effect of binaural beats on memory in contrast to 14 effect sizes that showed positive effects. Conversely, attention, anxiety, and analgesia subgroups did not reach significance in the test for heterogeneity, $Q(6) = 2.19$, $p = .90$, $Q(4) = 0.31$, $p = .99$, and $Q(2) = 4.69$, $p = .10$, respectively.

p-curve and *p*-uniform

To investigate the possibility of *p*-hacking, a *p*-curve analysis was performed. *p*-curve analysis investigates the *p* value distributions comparing them to the expected distributions to determine the presence of evidential values (van Aert et al., 2016). This method converts the *p* values for each study into z scores. Then, the sum of the z scores is divided by the square root of the number of *p* values obtaining an overall z score that is compared to a null of 33% power. Results obtained from the continuous test using the Stouffer method suggested evidential value for the overall studies, $z = -7.99$, $p < .001$ (full *p*-curve with $ps < .05$) and $z = -10.31$, $p < .001$ (half *p*-curve with $ps < .025$). *p*-curve analysis estimated that the mean power was 86%, 90% CI [71%, 94%]. As can be seen in Fig. 8, albeit slightly bimodal, results are right-skewed, thus suggesting the existence of evidential value. Five studies presented *p* values between .04 and .05, which indicates weak evidence of effectiveness. Furthermore, results from the *p*-uniform publication bias test did not reveal evidence of publication bias ($z = 0.23$, $p = .409$).

Fail-safe

Fail-safe *N* was calculated using the Rosenberg approach (Rosenberg, 2005), which takes into account the weighted average effect size, and suggested that it should be needed to add 554 nonsignificant studies to reduce the effect size and make results nonsignificant. Results can be considered strong against the file-drawer effect when fail-safe *N* is equal or greater than five times the number of studies plus ten (Rosenthal, 1991).

Meta-regression

To evaluate the extent to which different variables explained heterogeneity among the overall effect size, a weighted, linear mixed-effects regression was performed. We regressed the time under binaural-beat exposure, moment of exposure, and the type of sound used to mask the binaural beat between cases. Variance inflation factors were examined for

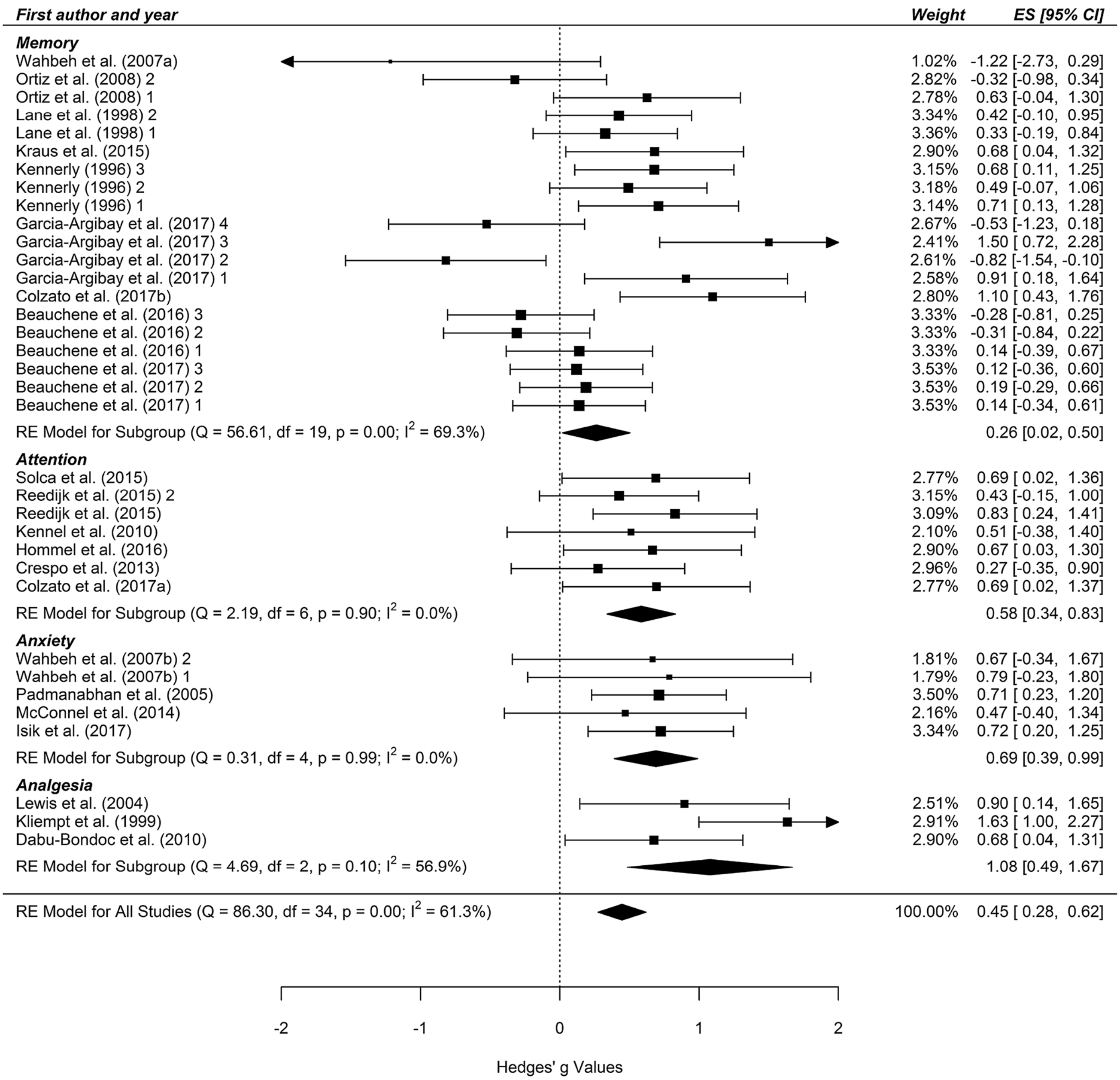

Fig. 7 Forest plots of effect size estimates divided by subgroups. Horizontal lines depict 95% CIs. Diamonds represent total effect sizes. The size of the squares varies according to the weight of each study in the analysis. *RE* random effects

all predictors on the effect sizes and observed no VIFs values greater than 2 nor any tolerance value lower than 0.5, which is less than the threshold of 10 and 0.1, respectively. The results from the Breusch–Pagan test confirmed that the assumption of homoscedasticity was met, $\chi^2(1) = 1.41$, $p = .235$. The assumption of normality was satisfied after visual inspection of the Q–Q plot.

Meta-regression showed that the moment of binaural-beat exposure is a reliable moderator of the relationship between the variations in effect sizes and binaural-beat usage, χ^2 $(2) = 16.17$, $p < .001$. The moment in which binaural-beat exposure took place accounted for a significant amount of between-study heterogeneity, yielding larger effects when the exposure was performed before or before and during the task ($b = 0.46$, $p = .006$; $b = 0.53$, $p = .002$, respectively) compared to when exposure occurred during the task (see Table 3). No differences were found between listening to binaural beats before or before and during the task ($p > .05$). The type of sound used to mask the binaural beat, as a whole, was not a significant predictor of effect sizes, $\chi^2(3) = 3.72$, $p = .293$. Unmasked binaural beats expressed larger effects compared to those masked with music ($b = 0.40$, p

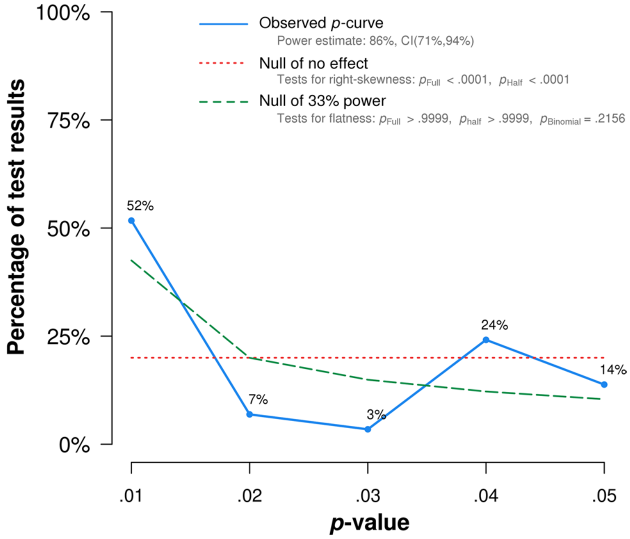

Fig. 8 Distribution of observed *p* values compared to the expected distribution of *p* values. The observed *p*-curve includes 29 statistically significant ($p < .05$) results, of which 18 are $p < .025$. There were six additional results entered but excluded from *p*-curve because they were $p > .05$

= .022), but similar to those masked with white noise or pink noise (*ps* > .05). No significant differences were found between the rest of the pairwise comparisons (*ps* > .05). These results suggest that binaural-beat induction is needed so as to increase its efficacy, and that there are no differences between whether the beat is masked with white noise, pink noise or unmasked. Additionally, the amount of time under binaural-beat exposure was a significant contributor to the model, $b = 0.01$, $\chi^2(1) = 5.77$, $p = .016$. Therefore, higher exposure times were associated with larger effect sizes. More precisely, a one-unit increase in exposure time (1 min) was associated with a 0.01 increase in effect size. Overall, the meta-regression model explained 56.8% of the total amount of variance (heterogeneity) accounted for by the moderators, $\chi^2(6)= 26.48$, $p < .001$. Moreover, an additional weighted, linear mixed-effects regression with the different binaural-beat frequencies as predictors reached significance, $\chi^2(6) = 13.29$, $p = .038$, $R^2 = .610$. Post hoc analysis indicated that multi-layered binaural beats displayed a larger effect compared to beta- and theta-frequency binaural beats (*ps* = .004 and .011, respectively). The rest of the pairwise comparisons were nonsignificant (*ps* > .05). Figure 9 depicts the differences in effect sizes by the different predictors.

Discussion

The purpose of this meta-analysis was to provide an overall estimate of binaural auditory beats effectiveness on two cognitive functions (memory and attention), anxiety, and analgesia. We intended to answer two questions: (a) what was the overall magnitude of the effectiveness of binaural-beat exposure on the selected outcomes, and (b) were there any binaural-beat attributes that systematically moderated this efficacy?

This meta-analysis provided robust evidence, although modest, regarding the efficacy of binaural beats on memory, attention, anxiety, and analgesia. Based on our results, we can observe that alpha (3 ESs), beta (10 ESs), gamma (1 ES), and theta (6 ESs) binaural-beat exposure affected the performance in memory tasks, and that the direction of this effect depended on the frequency used, being positive for the alpha, beta and gamma frequencies, and negative for the theta frequency (with the exception of studies 2 and 27). On the other hand, binaural beats consistently showed effectiveness in reducing the amount of intraoperative anesthesia. Both studies 10 and 21 applied multi-layered binaural beats, while study 25 did not report the frequency used. The efficacy of binaural beats in the reduction of anxiety scores after

Table 3 Results from the meta-regression analysis including moment of exposure, type of masking, and time under exposure as potential moderators

Variables	*b*	SE	*z*	*p*	95% CI	
					Lower bound	Upper bound
Type of masking						
Unmasked	0.40	0.18	2.30	.022	0.06	0.75
Pink noise	0.23	0.20	1.15	.252	− 0.16	0.62
White noise	0.32	0.24	1.36	.175	− 0.14	0.79
Music[a]						
Exposure time	0.01	0.00	2.40	.016	0.00	0.02
Moment of exposure						
Before and during	0.53	0.17	3.16	.002	0.20	0.86
Before	0.46	0.17	2.76	.006	0.13	0.79
During[a]						

[a]Reference category; *b* unstandardized coefficient, *SE* standard error, *z* ratio between the unstandardized coefficient and the standard error

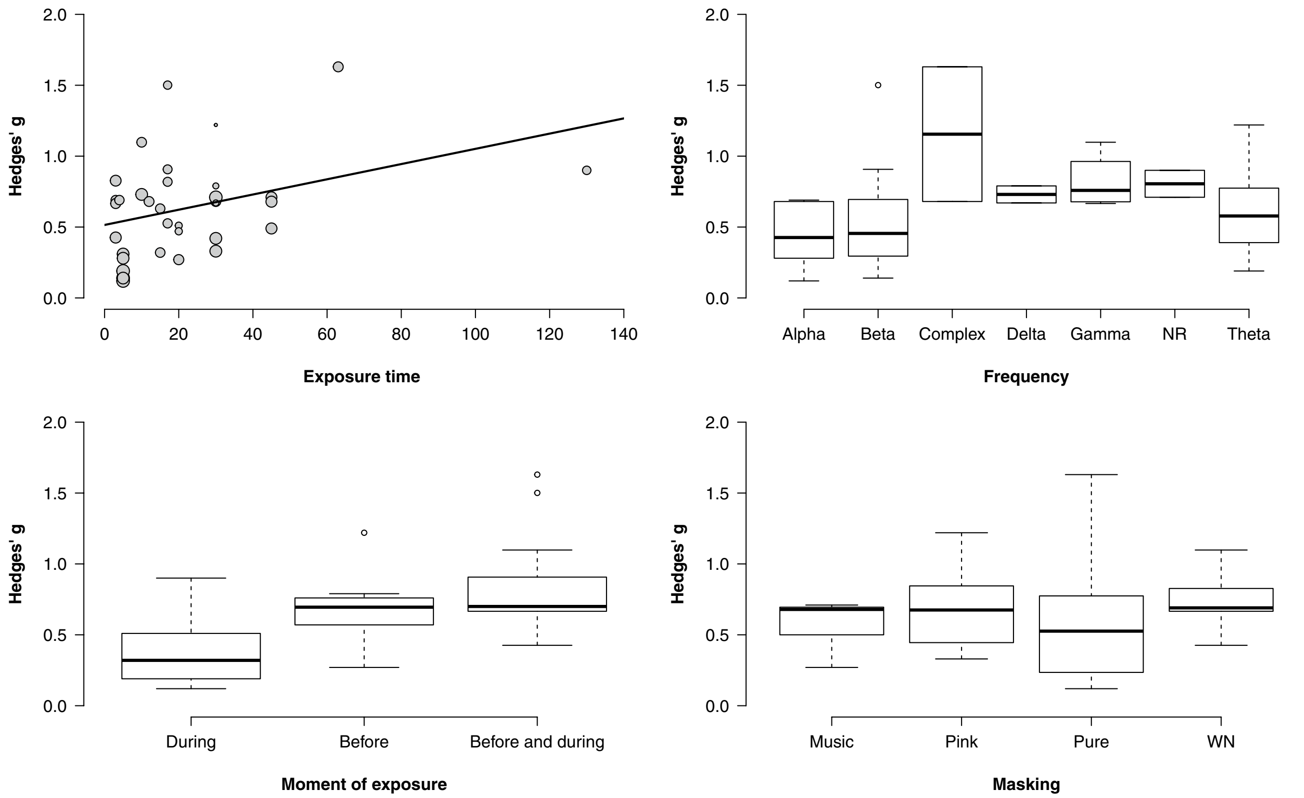

Fig. 9 Box plot of the of exposure time, frequency, moment of exposure, and masking variables. The size of each circle is inversely proportional to the variance (v_i) of each study effect size

delta/theta exposure has also been confirmed in all included studies ($k = 5$), although study 29 did not report the frequency used. Finally, attention was also affected by binaural-beat exposure. All studies ($k = 7$), excluding the study number 17, exhibited positive effects on attention utilizing alpha, beta, and gamma frequencies; based on our results, we can hypothesize that the reduced effectiveness observed in study 17 was caused by the moment of exposure—only during the task—and masking the binaural beat with music.

With respect to these potential moderator variables, results provided supporting evidence for the hypothesis that the moment of exposure plays a pivotal part in the effectiveness of binaural beats, showing a greater effect when exposure occurs before, and before and during the performance of a task. Additionally, it appears that the time under exposure does not produce a habituation to binaural beats as it was initially hypothesized (Vernon, Peryer, Louch, & Shaw, 2014). On the contrary, our results indicate a positive relationship between time under exposure and effect sizes, which in turn reflects that not only it is advisable to undergo an induction phase to ensure that the desired frequency is entrained by the time that the event or task to be measured begins, but also that time under exposure should be long enough to obtain the maximum benefit. In line with this suggestion, recent studies manifested that to provoke changes in almost all cortical regions, binaural-beat exposure should last for 9–10 min (Jirakittayakorn & Wongsawat, 2017; Seifi Ala, Ahmadi-Pajouh, & Nasrabadi, 2018). In regard to binaural-beat masking, our findings indicated that unmasked beats were associated with larger effect sizes compared with binaural beats masked with music, but no differences were found in comparison to pink noise or white noise. We can hypothesize that the reduced effectiveness observed with binaural beats embedded in music might be due to some interference between the frequencies present in the music and the binaural beat, as musical rhythms, even when they are not strictly periodic, have been reported to entrain body movement (London, 2004; McAuley, 2010; Phillips-Silver & Keller, 2012).

In relation to the binaural-beat frequency, our results denote that complex-frequency binaural beats (i.e., multi-layered) produced the largest effect. Due to the limited number of studies that have studied multi-layered binaural beats ($k = 3$), it is plausible that these results are only valid for surgical procedures and may not be generalizable to a broader range of applications such as memory enhancement or anxiety reduction. Future studies should address this question and determine whether the reduction in analgesia can be extrapolated to all types of surgical procedures and other areas of cognitive enhancement, and whether multi-layered binaural beats offer a greater effect than simple binaural beats.

Although most studies found significant differences between binaural-beat stimulation and the control conditions, it is necessary to identify why some studies could not find such differences. There are certain variables that could potentially explain interstudy differences in terms of effectiveness. For instance, one variable that might play a crucial role in binaural-beat effectiveness could be the carrier frequency, which should be investigated in future research to establish whether different frequency ranges produce different results. Other possible variables that might moderate the effectiveness of binaural beats, and that we have included in this meta-analysis, are the exposure time, the moment of exposure (i.e., before, during and before, and during the task), and the type of sound that was used to mask the binaural beat. Furthermore, we should not overlook the fact that there is a difference in the perception of binaural beats between males and females (Oster, 1973; Tobias, 1965) and that other inter-individual differences might be moderating the results. For instance, individual mesostriatal dopamine levels—indirectly measured by the spontaneous blink rate—have been found to determine the degree to which gamma binaural beats affect cognition (Reedijk et al., 2013; Reedijk et al., 2015). This could potentially be explained by a higher sensitivity and a more responsive mesostriatal dopaminergic system that initiates the neural processes more efficiently due to a hypodopaminergic state, which can be predicted by the spontaneous blink rate (Jongkees & Colzato, 2016). This higher sensitivity is prevalent in extraversion-related differences and implies an enhanced sensory reactivity such as lower auditory and noise thresholds (Smith, 1968; Stelmack & Campbell, 1974), and larger early visual event-related potential amplitudes like the N1 (Rammsayer & Stahl, 2004). In addition, introverts seem to be more responsive to induced changes in dopaminergic activity, while extroverts display a more efficient compensatory mechanism whereby homeostasis in neurotransmission is maintained (Rammsayer, Netter, & Vogel, 1993). Therefore, it is of paramount importance to determine how these variables affect the effectiveness of binaural beats and which the optimal carrier frequency is to be able to use the most effective parameters and thus make the most of the binaural beats. For the aforementioned reasons, the frequency of the binaural beats should be adjusted based on the sex of the listener to obtain similar and comparable results taking into account extraversion-related individual differences. Perhaps one way to reduce these extraversion-related differences might be to use carrier tones at higher frequencies where no significant differences in sensitivity between extroverts and introverts were observed (Stelmack & Campbell, 1974).

A number of limitations may have influenced the results obtained in the present meta-analysis. For instance, with the exception of study 29, the rest of the included studies had a modest sample size ($n < 70$) that can compromise the statistical power and the estimations by overrating binaural beats effectiveness. Publication bias is always a concern in meta-analysis, although the statistical tests carried out did not suggest the presence of publication bias. We cannot rule out the possibility that if we had included all the nonsignificant studies and, therefore, not published, the estimation of the effect sizes would have been potentially smaller. Moreover, a greater number of studies are necessary since, at present, there are a very small number of studies that investigated the practical applications of binaural beats. In addition, notwithstanding the importance of the carrier frequency, we could not include it in our analysis, as many of the included studies (33%) did not report such information. Following reporting guidelines is crucial to further advance in this field. Finally, due to the limited number of included studies ($k = 22$) interaction effects could not be examined and it is possible that the statistical power was not sufficient for conducting a meta-regression. The associations obtained in the meta-regression should be considered with caution since they possess a weaker interpretation capacity than those made from randomized comparisons due to their observational and not causal nature (Thompson & Higgins, 2002).

The results of this meta-analysis are encouraging and should be validated by larger sample size studies to ensure that the observed effectiveness can be replicated and applied to other areas such as implicit and episodic memory. On the other hand, the results obtained from the meta-regression should also be confirmed in future studies, as they are restricted insofar as the predictors were not theory driven. It is essential to validate the notion that exposure before, and before and throughout the task produces greater efficacy than just during the task. Taken together, these results suggest that binaural auditory beats affect memory, anxiety levels, attention, and perceived pain in a passive, automatic manner, and that the direction and the magnitude of the effect is determined by the binaural-beat frequency, moment and duration of exposure. The mechanisms behind how binaural-beat stimulation translates into psychophysiological changes are still unknown. Hence, further work in this area is needed and may lead to the development of a better understanding of it and new practical applications where binaural beats may exhibit further efficacy.

Compliance with ethical standards

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical approval Ethical approval was not needed for this meta-analysis.

Informed consent Informed consent was not required for this meta-analysis.

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