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REVIEW

Potential of binaural beats intervention for improving memory and attention: insights from meta-analysis and systematic review

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Abstract
Binaural beats (BB) entrainment is an auditory perceptual occurrence that exists when two tones of separate frequencies are simultaneously presented to each ear. Research on BB entrainment has gained attention due to its ability to treat various conditions like anxiety, attention-deficit/hyperactivity (ADHD), etc. Even though research on BB entrainment suggests its efficiency in improving cognition among individuals, existing literature indicates mixed results in the cognitive domains of attention and memory. Thus, we conducted meta-analysis to examine the effect of BB intervention on memory and attention, respectively, in the current paper. We further performed a systematic review on the selected studies to report their variables, demographic characteristics of the participants, and outcomes to comprehensively position the research on BB intervention exclusively in the areas of memory and attention. Fifteen studies met our inclusion criteria. Based on 31 effect sizes, the results indicated an overall medium and significant effect size ($g = 0.40$). Findings from systematic review reveal conflicting results, especially concerning theta and beta's efficacy on memory (recall and recognition tasks) and attention-related tasks. The findings of the current paper add to the growing evidence that BB intervention improves attention and memory in humans. Since the findings suggest a near-moderate effect of BB interventions and mixed results in the systematic review, more research with robust study designs must explore its guiding principle and the expanding role of brainwaves in improving memory and attention in individuals. Such an intervention has important implications in both clinical and non-clinical settings.

Introduction

Binaural beat (BB) entrainment is a topic of great interest for many researchers in the field of psychology. The theoretical underpinnings coupled with practical implications led to its utilization to treat various conditions, like anxiety, pain, learning disorders, attention, intelligence, and memory (Basu & Banerjee, 2020; Crespo et al., 2013; Garcia-Argibay et al., 2019a, 2019b; Olmstead, 2005). Discovered by Heinrich Wilhelm Dove in 1839, binaural beats are auditory sensations that occur when sinusoidal waves of two different frequencies are presented simultaneously to each ear (Sharma et al., 2017). The sound presented to each ear is processed individually, leading to a perceived single sound consisting of the frequency intermediate to the two different frequencies (Garcia-Argibay et al., 2019a). For example, if we present 120 Hz in the right ear and 130 Hz in the left ear, then the perceived sound will have a frequency of 10 Hz. The process of integrating two pure tones of different frequencies into one perceived frequency is called binaural integration (Garcia-Argibay et al., 2019b).

Neurophysiological research suggests that BB can be measured in the cerebral cortex through electroencephalography (EEG) as a frequency following response (FFR), after it originates in the superior olivary nuclei and the brainstem (Garcia-Argibay et al., 2019a, 2019b). EEG studies suggest that BB can affect the electrocortical activity, that is, modulate the frequency of the neuronal oscillations without any prior training (Garcia-Argibay et al., 2019a, 2019b; Norhazman et al., 2012; Teplan et al., 2006). Specific oscillations or frequency bands are linked to certain states of consciousness that can lead to behavior changes in humans (Sharma et al., 2017). For instance, delta range (1–4 Hz) is associated with sleep, theta range (4–8 Hz) promotes slow

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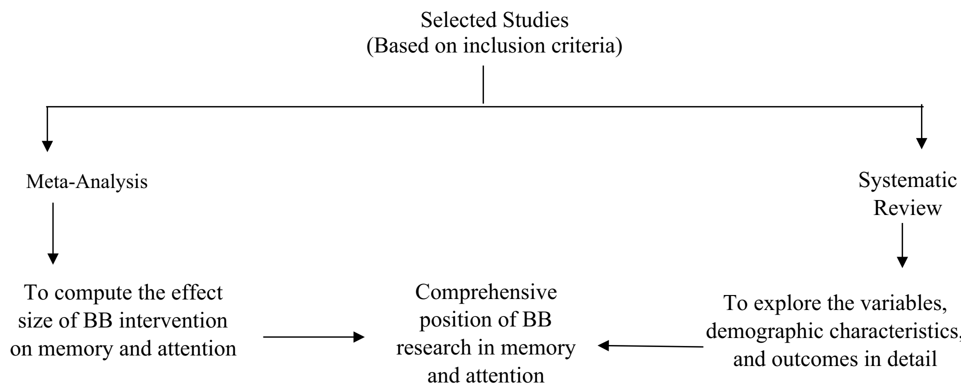


Fig. 1 Study design

brain activities that promote sleeping or dreaming, alpha (8–13 Hz) promotes relaxation and meditative state, and beta (16–25 Hz) relates to higher vigilance and concentration (Crespo et al., 2013). The possibility that BB entrainment can alter behavioral states through modulating neuronal oscillations can be utilized to promote optimal functioning of cognitive and emotional processes in both clinical and non-clinical populations.

Crespo et al. (2013) suggested that the ability of humans to hear BB depends on evolutionary assimilation, although some species can detect BB based on their skull sizes. Nevertheless, most BB entrainment studies have concentrated on alpha, beta, theta, and gamma frequency bands. Further, there is growing support that BB entrainment can lead to psychophysiological changes, especially in the areas of anxiety, creativity, attention, and memory (Garcia-Argibay et al., 2019b). For instance, Padmanabhan et al. (2005) suggested the potential of BB audio in producing anxiolysis that reduces anxiety during surgical/medical procedures. Similarly, Weiland et al. (2011) also asserted the efficiency of BB audio in reducing anxiety. Alpha and gamma BB entrainment further improved divergent thinking and creativity (Reedijk et al., 2013). Even though some studies have suggested significant improvements on attention and memory tasks (Colzato et al., 2017; Kraus & Porubanovà, 2015; Ortiz et al., 2008), other researchers have not been able to establish the effectiveness of BB entrainment in related areas, especially in attentional tasks (Crespo et al., 2013; Kennel et al., 2010). The limited studies conducted on clinical population (for example, Attention-Deficit/Hyperactivity Disorder [ADHD]) also show mixed results (Kennel et al., 2010). These results can be due to the differences in experimental methods, such as duration of the entrainment, frequency range, and comparison conditions (Garcia-Argibay et al., 2019b).

The available literature on BB entrainment shows mixed results and restricts the generalizability of the overall findings and their related implications. Therefore, the aim of the current paper was to explore the effect of BB on cognitive domains, such as memory and attention. These cognitive domains are inter-dependent (Chun & Browne, 2007) and have important implications in daily life, including educational settings (Schacter, 2013). For instance, working memory variations among children have been found to be related to their academic performances in subjects, like mathematics and science (Gathercole et al., 2016). Daily activities, like driving, also requires a successful interplay of working memory and attention (Watson et al., 2016). In addition, due to memory's limited capacity, attention determines the encoding process; and memory, especially from past events, guides the attention process (Chun & Browne, 2007). We conducted meta-analysis to evaluate the degree to which BB entrainment affects memory and attention, along with systematic review to closely examine the selected study's variables, methods, entrainment duration, and sample characteristics. The systematic review provides a more comprehensive picture on BB's efficiency on individual's attention and memory domains. The findings of this study will assist in understanding the position of research of BB entrainment on memory and attention along with its related implications.

Methods

We conducted meta-analysis according to the Meta-Analysis Reporting Standards (MARS) of the American Psychological Association (Cooper, 2015) and systematically reviewed the selected studies in accordance with the PRISMA[1] guidelines. Figure 1 depicts the study design.

Search strategy

We used search engines, like Google Scholar, PubMed, and Science Direct, to perform a systematic search to identify the relevant studies. We limited the search to English language

[1] Preferred reporting items for systematic reviews and meta-analyses.

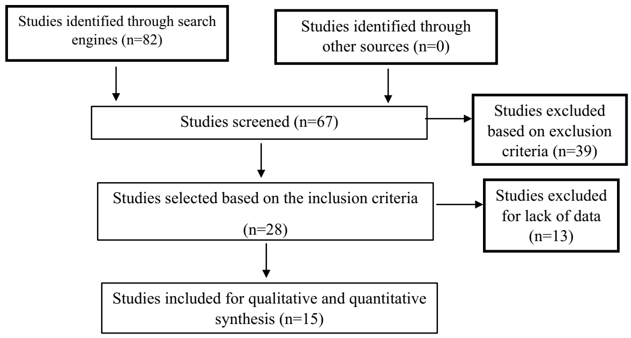


Fig. 2 Flowchart depicting the process of selection of research studies

papers only with keywords, such as "binaural beats," "binaural beat entrainment," and "BB entrainment" to explore the studies till March 2022.

The search resulted in 67 studies, of which 39 studies were excluded since they did not meet the inclusion criteria. Thirteen additional studies were excluded as they reported insufficient data for conducting meta-analysis. Thus, 15 studies were finally included in the sample pool.

Figure 2 shows the process of selecting relevant studies. The first author reviewed the selected papers and compared them in terms of their methodology, participant's demographic characteristics, and outcomes. This systematic review supports the meta-analysis findings of the selected studies.

Inclusion and exclusion criteria

The studies had to fulfil the following criteria to be included in the meta-analysis and systematic review: (a) access to the complete paper; (b) experimental studies; (c) BB as the treatment or independent variable; (d) English language papers; (e) application of BB in the memory and attention domains; and (f) provided sufficient information to calculate the Effect Sizes (ES) from descriptive or inferential statistics. The studies that did not provide sufficient information on its methodology or meet the inclusion criteria were excluded from this study. Further, we did not include any geographical or time (year of the study) constraint for extracting studies from the search engines.

Operational characteristics of independent and dependent variables

1. Binaural beat entrainment is the independent variable (IV). It is the entrainment induced by BB wherein two different pure tones are presented to both ears (Ross & Lopez, 2020). For example, 240 Hz and 260 Hz presented to the left and right ears, respectively, to produce entrainment of 20 Hz.
2. Attention is one of the dependent variables (DV). It is a type of cognition that includes an overall consciousness (through focus and concentration) and active engagement with the surroundings (Crespo et al., 2013). For our analysis, we have included studies with attentional blink tasks (Ross & Lopez., 2020) along with tasks requiring concentration and focus for both clinical and non-clinical samples (Crespo et al., 2013; Kennel et al., 2010).
3. Memory is another DV. It is a type of cognition that acquires, stores, and retrieves information (Zlotnik & Vansintjan, 2019). For our analysis, we have included all aspects of memory, including long-term and episodic memory (Garcia-Argibay et al., 2019b; Roberts et al., 2018), working memory (Beauchene et al., 2017), and verbal memory (Ortiz et al., 2008).

Data extraction

We extracted the following information from the selected studies for meta-analysis: research topic, authors, year of publication, variables, research objective, sample characteristics, duration of exposure, type of control or alternate sound for masking binaural beats (if any), and measure of outcome.

Quality assessment

The first author conducted a quality assessment for each potentially relevant study before including them for the final analysis. The quality assessment was based on the following methodological questions: (a) randomization or double blinding; (b) sample characteristics; (c) presence of control or a comparison group or a baseline measurement; (d) detailed process of the BB intervention; and (e) validity of assessments to measure the outcome variables (Garcia-Argibay et al., 2019b). Only those studies that reported the information mentioned above were included for the final meta-analysis.

Statistical methods

Effect size calculation

Since most studies had a small sample size and continuous outcome variables, we used Hedge's g to calculate the effect sizes of each outcome of the study (Harrer et al., 2019). If the study had more than one outcome, we used a separate table to calculate their effect sizes (Basu, 2017). In some studies, the effect size was drawn from the mean differences and standard deviations, while in other cases, it was drawn from the respective p (independent t tests) and f values (one-way ANOVA tests). Table 1 summarizes the

Table 1 Study, subgroup, Ne, Nc, Hedge's *g*, and variance of the effect size

Study	Subgroup	Ne	Nc	Hedge's g	Variance
Garcia-Argibay et al., 2019a, b	Memory	16	16	0.9031	0.1384
Garcia-Argibay et al., 2019a, b	Memory	16	16	−0.8197	0.136
Roberts et al., 2018	Memory	25	21	2.1968	0.1419
Roberts et al., 2018	Memory	20	20	2.4976	0.1812
Beauchene et al., 2017	Memory	34	34	0.1828	0.0591
Beauchene et al., 2017	Memory	34	34	0.121	0.0589
Beauchene et al., 2017	Memory	34	34	0.0846	0.0589
Kraus & Porubanovà, 2015	Memory	20	20	0.6819	0.1061
Ortiz et al., 2008	Memory	18	18	−0.319	0.1126
Ortiz et al., 2008	Memory	18	18	0.4059	0.1135
McMurray, 2006	Memory	20	20	0.6332	0.1052
Kennerly, 1994	Memory	27	23	0.6982	0.0855
Kennerly, 1994	Memory	27	23	0.4916	0.083
Kennerly, 1994	Memory	27	23	0.6703	0.0852
Ross et al., 2020	Attention	14	13	0.0784	0.1485
Ross et al., 2020	Attention	14	13	1.4492	0.1897
Ross et al., 2020	Attention	14	13	0.3025	0.1502
Hommel et al., 2016	Attention	20	20	0.645	0.1054
Solcà et al., 2016	Attention	18	18	1.8089	0.1586
Reedijk et al., 2013	Attention	24	24	0.56	0.0867
Reedijk et al., 2013	Attention	24	24	0.2882	0.0842
Colzato et al., 2017	Attention	18	18	0.6687	0.1176
Crespo et al., 2013	Attention	20	20	0.1855	0.1004
Kennel, 2010	Attention	10	10	0.5482	0.2082
Kennel, 2010	Attention	10	10	−0.1074	0.4476
Kennel, 2010	Attention	10	10	0.3594	0.2035
Kennel, 2010	Attention	10	10	−0.2184	0.2013
Kennel, 2010	Attention	10	10	−0.4698	0.206
Kennel, 2010	Attention	10	10	0.1749	0.2008
Kennel, 2010	Attention	10	10	0.8466	0.2195
Engelbregt et al., 2021	Attention	25	25	0.6888	0.0847

study, subgroup, sample sizes (participants in experimental and control conditions), Hedges' *g*, and variance of the effect size for the included studies in the meta-analysis.

Analysis

All computations were conducted in the RStudio software version 3.4.1. The R codes for the analysis are attached in Appendix. The computations for the effect sizes were conducted using the *compute.es* package. We estimated effect size *g* and its variance for each study using the *meta* package. A random-effects model with Restricted Maximum Likelihood Estimation (REML) was computed since the treatment effects of the selected studies were not identical in the population (Harrer et al., 2019). The treatment effects varied in terms of duration of the BB intervention, frequencies, and comparison tones. REML estimations were utilized as they do not underestimate the variance (Garcia-Argibay et al., 2019b; Thompson & Sharp, 1999).

Further, we conducted a moderator analysis to evaluate whether the entrainment effect differs between attention and memory studies (Polanin, 2021). We installed the *metafor, dplyr, robumeta, and clubSandwch* packages. Moderator analysis was also conducted on the moderators identified through systematic review of the selected studies, such as frequency of the intervention, masking noise, entrainment type, and number of participants in the experimental and control groups. The findings of the moderator analysis assisted in providing information regarding the moderator's statistical significance. Meta-regression was also conducted to examine the relationship between the multiple variables in the selected studies and their effect sizes, using the REML estimator (Polanin, 2021).

The probable influence of publication bias was assessed with the funnel plot and Egger's test of the intercept (Harrer et al., 2019). To visualize a lack of studies with small effect sizes, we generated a funnel plot on RStudio software, using *funnel()*. To quantify the funnel plot, we performed the Egger's test using the *dmetar* package.

The findings are discussed in light of both systematic review and meta-analysis of the selected studies.

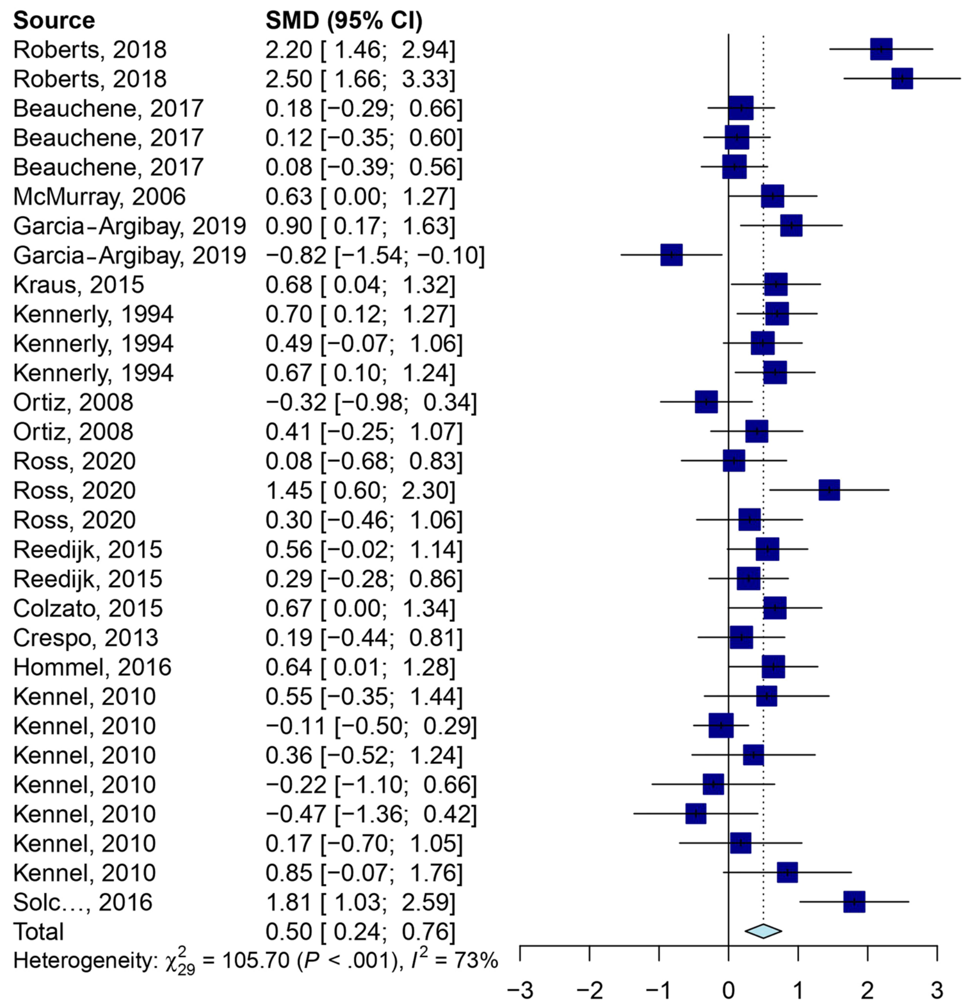
Findings

Meta-analysis

The random-effects model provided an effect size of $g = 0.4033$, 95% CI [0.1389; 0.6677]. Figure 3 displays the forest plot of effect sizes of the selected studies. The test for heterogeneity of the studies suggested a high amount of heterogeneity, Q $(df = 32) = 121.344$, $p < 0.0001$, $I^2 = 76.91\%$. Further, the moderator analysis does not show any variability in terms of the effects of BB intervention on memory and attention studies, respectively ($p > 0.05$).

Findings from the statistical test of moderations indicate significant effects of the frequency of the intervention, masking noise, and entrainment type. Under frequency of the intervention, only alpha frequency showed significant results ($p < 0.05$), among the other frequencies, such as alpha and beta, beta only, theta and beta, and gamma only. In masking noise, beta frequency indicates significant results ($p < 0.05$), whereas other factors, such as constant tone, monaural beats, non-binaural beats, pink noise, sea sound, pure tone, and classical music suggest non-significant results. Under the entrainment type, significant results were obtained by factors, such as entrainment before and after the task ($p < 0.001$), between encoding and retrieval

Fig. 3 Forest plot



($p < 0.0001$), and entrainment given during the task ($p < 0.05$). However, entrainment given before the task, and before and during the task showed non-significant results. Number of participants in control and experimental groups did not produce significant results. In summary, intervention efficiency is influenced by moderators, such as alpha-only entrainment frequency, beta frequency as a masking noise, and entrainment design, that is, given before-after or between encoding-and-retrieval as well as during the task (Stee & Yang, 2020).

To evaluate the relationship between the different variables in the selected studies and their respective effect sizes, we conducted a linear mixed-effects meta-regression. Since the demographic characteristics of the participants were similar in all studies, we only regressed the entrainment frequency type, masking noise, duration of the entrainment, entrainment design, and number of participants in the study. The findings from meta-regression are summarized in Table 2. They suggest that the entrainment frequency type and masking noise majorly accounted for the between-study heterogeneity. Overall, the meta-regression model explained 3.71% of the total amount of variance accounted by the moderators.

Even though Egger's test of intercept did not reveal any significant publication bias ($p = 0.283$), Fig. 4 shows a substantial publication bias in the studies included in the meta-analysis since many small-sample studies show unexpectedly high effect sizes. This potential substantial publication bias could be due to the non-availability of unpublished studies on binaural beats, attention, and memory. The overall results suggest a near-moderate effect of binaural beat entrainment on an individual's attention and memory domains.

Systematic review

Out of the 15 selected studies, six examined memory, eight examined attention, and one examined both memory and attention. Tables 3 and 4 contain the characteristics of the selected studies in the areas of memory and attention, respectively.

Table 2 Findings of meta-regression analysis

Variables	estimate	SE	*z*	*p*	CI	
					Lower bound	Upper bound
Entrainment frequency						
Beta	−5.1962	1.9994	−2.5989	0.0094	−9.1150	3.4497
Gamma	−6.5545	3.1067	−2.1098	0.0349	−12.6435	3.4497
Theta and beta	−7.2722	3.4893	−2.0841	0.0371	−14.1111	3.4497
Masking Noise						
Constant tone	−2.8410	1.3422	−2.1166	0.0343	−5.4718	3.4497
Pink noise	−5.0700	3.0824	−1.6449	0.1000	−11.1114	3.4497
Sea sound	−1.8156	0.5330	−3.4065	0.0007	−2.8602	3.4497
White noise	−2.1878	1.2487	−1.7520	0.0798	−4.6353	3.4497
Number of participants						
Experimental	3.6692	2.1536	1.7038	0.0884	−0.5517	3.4497
Control	1.7771	1.3887	1.2797	0.2007	−4.7861	1.7678
Entrainment design						
Before and during task	−2.9091	2.2258	−1.3070	0.1912	−4.7861	1.7678
Before the task	1.0384	0.8500	1.2216	0.2219	−4.7861	1.7678
Between encoding and retrieval	2.5132	0.7064	3.5580	0.0004	−4.7861	1.7678

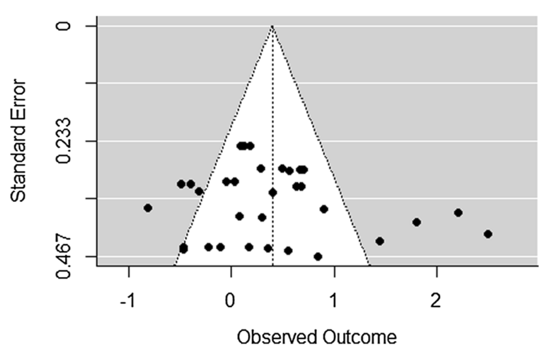


Fig. 4 Funnel plot

Studies on memory

The studies emphasized working memory (Kraus & Porubanovà, 2015; Beauchene et al., 2017), episodic memory (Roberts et al., 2018), long-term memory (Garcia-Argibay et al., 2019a), and verbal memory (Ortiz et al., 2008). These studies included alpha, beta, and theta binaural beats. The frequency of the binaural beats ranged from five to 20 Hz. Further, the duration of each entrainment session lasted from 12 to 36 min (Kraus & Porubanovà, 2015; Roberts et al., 2018). The control conditions comprised white noise (Garcia-Argibay et al., 2019a; Ortiz et al., 2008; Roberts et al., 2018), music without BB (Beauchene et al., 2017; Kennerly, 1994; McMurray, 2006), overlapping sounds (Kraus & Porubanovà, 2015), and classical music (Beauchene et al., 2017). According to the moderator analysis, none of the control conditions showed any significant results, that is, these moderators do not influence the intervention effects.

While most studies had a non-clinical, adult population, only two studies comprised adolescents (14 years) and senior citizens (over 65 years), respectively (Garcia-Argibay et al., 2019a; McMurray, 2006). One study consisted of a clinical population, that is, individuals diagnosed with ADHD (Kennerly, 1994). In studies with only an adult sample, the age ranged from 18 to 51 years.

McMurray's work (2006) on healthy aging individuals showed higher memory function in the forward digit span test due to the alpha BB intervention. Improvements were also found in participant's working memory capacity following alpha frequency BB stimulation (Kraus & Porubanovà, 2015). Moderator analysis of entrainment frequency also showed significant effect of alpha frequency ($p < 0.05$), suggesting an increased efficiency of alpha frequency on entrainment effects. Kennerly's investigation (1994) on the effects of beta frequency BB entrainment on memory tasks in the ADHD sample suggested improved free recall and digit span tasks. However, the improvement in the recognition task was not significant. A recent study showed participant's improved performances on visuospatial and working memory tasks after beta frequency BB intervention compared to control, alpha, and theta conditions (Beauchene et al., 2017). However, Ortis et al. (2008) concluded that theta frequency binaural beat stimulation improved recall compared to white noise and beta frequency. Further, source memory retrieval was also significantly higher in the theta BB entrainment than control conditions and alpha entrainment (Roberts et al., 2018). On the other hand, performances in recall and recognition tasks showed higher improvements after beta frequency BB stimulation as compared to the theta frequency stimulation and control conditions

Table 3 Characteristics of the selected studies on memory

Study	Objective	Participant Type	Total number of participants	Age Group/mean age	Frequency used	Entrainment duration	Control Comparison	Results
Garcia-Argibay et al., 2019a, b	To determine the effect of BB on long-term memory	Non-clinical	32 14–51		Beat and theta	15 min	White Noise	Beta frequency binaural beat stimulation improved recall and recognition tasks
Roberts et al., 2018	To observe improved source memory performance and enhanced theta activity during source memory retrieval after theta oscillation intervention	Non-clinical	90 18–26		Beta and theta	36 min	White noise	Source memory retrieval was significantly higher only in the theta entrainment
Beauchene et al., 2017	To determine the effects BB have on the recorded EEG frequency responses and cortical connectivity, using graph theory methods, during a cognition task	Non-clinical	34 18–46		Theta, alpha, and beta	5 min for each frequency band	No stimulation, Pure Tone, and Classical Music	Only beta frequency binaural beats increased performance in visuospatial and verbal working memory tasks
Kraus & Porubanovà, 2015	To explore possible temporary improvements in working memory consequently of alpha range BB stimulation	Non-clinical	40 $M = 21.63$		Alpha	12 min	Overlapping sounds (sea waves)	Working memory capacity improved following alpha-frequency bb stimulation
Ortiz et al., 2008	To establish whether stimulation at 5 Hz enables immediate words recall	Non-clinical	18 $M = 29.83$		Theta and beta	15 min (2 sessions per workday for 15 days)	White noise	Theta frequency binaural beat stimulation improved recall
McMurray, 2006	To compare the effect of auditory BB on measures of neurocognitive function and on brainwave activity	Non-clinical	20 67–80		Alpha	Duration of the neurocognitive task	Soft music without BB	Participants exhibited significantly higher memory function during the binaural beat phase

Table 3 (continued)

Study	Objective	Participant Type	Total number of participants	Age Group/mean age	Frequency used	Entrainment duration	Control Comparison	Results
Kennerly, 1994	To question the effectiveness of BB's in facilitating memory under controlled conditions	Clinical condition (ADHD)	48	Undergraduate students (age N.A.)	Beta	15 min before the task + duration of the task	Music without BB	Improved free recall but not recognition

(Garcia-Argibay et al., 2019a). Moreover, these findings suggest that theta BB may impair cognitive performance (recall and recognition) due to their association with relaxation, meditative state, and decreased activation levels. Apart from alpha-only frequency, the present moderator analysis suggests non-significant effects of frequencies of alpha and beta, gamma only, and theta and beta, respectively.

From these studies, we observe that different brainwave frequencies affect various aspects of memory and to varying degrees. While some findings suggest a more significant effect of beta BB entrainment on working memory (compared to alpha entrainment), others show the efficiency of theta BB entrainment on recall, including source memory retrieval (as compared to beta and alpha entrainment). We also observe conflicting findings in terms of theta and beta's efficacy on recall and recognition tasks, which further question the generalizability of the findings of such entrainment sessions. However, there is no doubt that all frequencies (alpha, beta, and theta) seem to have some influence on our working memory domains.

Studies on attention

Eight studies investigated the effect of BB stimulation on an individual's attentional capacities. These studies majorly emphasized attentional blink tasks (Reedijk et al., 2013; Ross & Lopez, 2020), dual-task paradigm (Hommel et al., 2016), and attentional capacities (Crespo et al., 2013; Engelbregt et al., 2021; Kennel et al., 2010). They were conducted with gamma, beta, alpha, and theta frequencies. The frequency ranged from four to 40 Hz. Four out of the eight studies conducted experiments with gamma BB (40 Hz), although with different durations (Colzato et al., 2017; Engelbregt et al., 2021; Reedijk et al., 2013; Ross & Lopez, 2020). The duration of each entrainment session lasted from three to 20 min.

Most studies consisted of non-clinical, adult (above 18 years) population. Only one study administered BB intervention on clinical population (ADHD) of age ranging from eight to 21 years (Kennel et al., 2010). The control conditions included constant tone of 340 Hz (Colzato et al., 2017; Hommel et al., 2016; Reedijk et al., 2013), soundtrack without BB or self-made audio (Crespo et al., 2013), pink noise without BB (Engelbregt et al., 2021; Kennel et al., 2010), and monaural beats (Engelbregt et al., 2021; Solcà et al., 2016). One study conducted beta frequency BB as a comparison condition (Ross & Lopez, 2020). Moderator analysis suggests the significant effects of beta frequency and monaural beats on the intervention results.

Entrainment of gamma frequency BB improved attentional control by terminating the attentional blink phenomenon and false responses (Flanker test) in participants (Engelbregt et al., 2021; Reedijk et al., 2013). After listening

Table 4 Characteristics of the selected studies on attention

Study	Objective	Participant type	Total number of participants	Age group/mean age	Frequency used	Entrainment duration	Control comparison	Results
Ross et al., 2020	To investigate whether BB stimulation could accelerate the training outcome in an attentional blink (AB) task	Non-clinical	27	18–32	Gamma and beta	15 min	Beta frequency	Gamma stimulation accelerates the AB training outcome
Hommel et al., 2016	To explore if BB in the gamma range bias the cognitive-control style toward flexibility	Non-clinical	40	18–27	Gamma	3 min before the task + duration of the task	Constant tone of 340 Hz	Participants, after entrainment, demonstrated cognitive flexibility
Solcà et al., 2016	To explore if BB synchronize activity between hemispheres both at the neural and at the behavioral level	Non-clinical	18	21–32	Alpha and theta	3 min	Monaural beats	Performances on digit tasks improved after alpha and theta bb entrainment sessions
Reedijk et al., 2013	Investigated the effect of BB on attentional control in an AB task	Non-clinical	24	17–25	Alpha and gamma	3 min before and during the AB task	Constant tone of 340 Hz	Entrainment of gamma frequency bb improved attentional control by terminating the AB phenomenon in participants
Colzato et al., 2017	To investigate the effect high frequency BB on attentional control in an AB task	Non-clinical	36	18–28	Gamma	3 min before and during the global–local task	Constant tone of 340 Hz	Gamma bb on increases attentional focus in participants
Crespo et al., 2013	To explore the potential of BB in tasks that require focus and concentration	Non-clinical	60	$M = 28.9$	Theta and beta	20 min	Identical soundtrack without bb and a self-made audio including several layers of BBs	No significant differences between the experimental and control groups in the attention tests
Kennel, 2010	To explore the potential for the use of BB stimulation to reduce the symptom of inattention in children and adolescents with ADHD	Clinical	20	8–21	Beta	20 min, three times a week	Pink noise	No significant improvement on attention tasks

Table 4 (continued)

Study	Objective	Participant type	Total number of participants	Age group/mean age	Frequency used	Entrainment duration	Control comparison	Results
Engelbregt et al., 2021	To examine the effect of 40 Hz BB and monaural beats (MB) on attention and EEG	Non-clinical	25	$M=21.8$	Gamma	5 min	Pink noise, monaural beats	40 Hz BB improves attention but do not show the occurrence of neural entrainment

to gamma BB, participants further demonstrated cognitive flexibility (Hommel et al., 2016). This suggests that BB with gamma frequency can improve an individual's ability to shift between tasks to achieve the appropriate problem-solving strategy (Garcia-Argibay et al., 2019b). Colzato et al. (2017) also affirmed the effectiveness of gamma BB on increasing attentional focus in participants. Further, Ross and Lopez (2020) suggested that gamma stimulation (40 Hz), when conducted during attentional blink training, accelerates its outcome. The findings also suggest against immediate improvement. Instead, the improvement becomes evident only after consolidation during sleep. However, Engelbregt et al. (2021) found no difference in the reaction time among participants exposed to BB, monaural beats, and pink noise.

Theta and beta BB stimulation on individuals diagnosed with ADHD showed no significant improvement on attention tasks (Kennel et al., 2010). Crespo et al. (2013) also did not find any significant differences between the experimental and control groups in the attention tests after entraining the former with commercially available theta and beta BB. In addition, the findings from moderator analysis did not suggest any significant effects of theta and beta BB on intervention's efficacy. However, Solcà et al. (2016) demonstrated improved performances on digit tasks after alpha and theta BB entrainment sessions compared to the baseline. But no significant difference between monaural and BB stimulations was observed from the findings.

These findings suggest a significant effect of majorly gamma-induced BB intervention on attention compared to theta, alpha, and beta frequencies. Conflicting result regarding theta frequency's efficacy on attentional tasks is also observed. Alpha-induced BB, although improved performances on attentional tasks (Solcà et al., 2016), has not been extensively studied. This could be due to the association of the alpha range with non-attentional domains, like wakeful relaxation (Bergland, 2015).

From the overall findings, we can deduce that the studies on BB's efficiency on memory and attention domains show mixed results. The meta-analysis data further suggests a near-moderate effect of BB on these domains.

Discussion

The purpose of the current paper was to explore the efficiency of BB entrainment on memory and attention, through meta-analysis, and support the findings through systematic review of the selected studies. We intended to answer the following questions: (a) what the overall effect (quantitative) of BB entrainment on the selected outcomes was; (b) was there a difference in BB effect on memory and attention; and (c) what the attributes in the selected studies were, that could possibly moderate the effect of BB entrainment on the outcomes.

The results based on 31 effect sizes suggested a moderate effect size ($g = 0.40$). Findings from moderator analysis further indicated no significant differences, in terms of BB effects, between memory and attention studies. The statistical tests of moderations suggest the significant effects of alpha-only entrainment, beta frequency as the masking noise, entrainment given before-after the task or between encoding and retrieval, or during the task on the efficiency of the BB intervention. Additionally, meta-regression suggests the moderating effect of variables, like frequency of BB entrainment, masking noise, and entrainment type on the effect sizes of the selected studies. In masking noise, only beta frequency was a significant indicator, unlike pink noise, constant tone, white noise, pure tone, monaural beats, and sea sound. However, previous studies suggest that the overall masking noise did not contribute significantly to their model (Garcia-Argibay et al., 2018). The previous and the current findings are also dissonant in terms of the exposure of BB stimulation. This incongruency could be due to the differences in the selected studies and the area of research, that is, cognition, anxiety, and pain in the previous research as compared to memory and attention in the current study. Nonetheless, in terms of entrainment type, the current findings are in line with previous research, suggesting that exposure of BB stimulation before the task does not make any difference (Garcia-Argibay et al., 2018).

Findings from systematic review indicate that theta and beta frequencies exert a profound effect on working memory, especially in retrieval studies (Beauchene et al., 2017; Garcia-Argibay et al., 2019a). Alpha BB intervention also improved memory functions, including working memory capacity (Kraus & Porubanovà, 2015; McMurray, 2006). Even though all frequency bands (alpha, beta, and theta) seemed to exert an effect on memory functions, comparison studies show conflicting results in terms of which frequency range has a better effect on the same (Beauchene et al., 2017; Ortis et al., 2008). The findings from the meta-regression further support this notion given the differences in their significance levels.

Attention studies suggest a dominant effect of gamma frequency BB on attentional blink (AB) and related tasks (Colzato et al., 2017; Reedijk et al., 2013). Wherein studies with alpha BB are limited even after improving performances in attention-related tasks (Solcà et al., 2016), conflicting evidence is found against beta and theta's efficacy on improving attention (Crespo et al., 2013; Kennel et al., 2010; Solcà et al., 2016).

It is important to note that the nature of the brainwaves has an important role in determining the behavioral outcomes, especially in cognitive tasks, like memory and attention. For instance, theta waves can be associated with processing of new (episodic) information, beta waves reflect cognitive control, and gamma waves can be associated with perceptual and cognitive processes (Klimesch, 2012). Further, alpha waves, due to its nature of inducing relaxed state in individuals, may not play a pivotal role in tasks-related attention (Bergland, 2015). For example, a study conducted in Massachusetts Institute of Technology (MIT) improved attention capacities in individuals by suppressing alpha waves through neurofeedback training (Trafton, 2019).

Some brainwaves may also work in tandem to improve performances in cognition-related tasks. Alekseichuk et al. (2016) observed improved working memory performances when high gamma oscillations coincided with peaks of theta waves. Similarly, both alpha and theta waves have been associated with visual attention (Singh & Narang, 2014). EEG studies further suggest the coexistence of brainwaves in different parts of the brain during cognition-related tasks. For instance, Singh and Narang (2014) observed a decrease in alpha waves in EEG channels (AF3 and F7) and an increase in beta waves (F8 and AF4) during performances on attentional tasks. For working memory, alpha and theta waves also coexist in different parts of the brain (Singh & Narang, 2014). That is, theta increases in the frontal region, whereas alpha increases in the posterior and bilateral areas of the brain. These findings suggest a functional interplay between different frequencies during a cognitive task which is contrary to the traditional approach of examining strictly defined frequency bands (Klimesch, 2012). Thus, the conflicting findings from the selected studies on attention and memory can be resolved by examining the interplay between the frequency bands (theta and beta) to eliminate any ambiguity.

The differences in research designs can also lead to differences in the results obtained by the researchers. Garcia-Argibay et al. (2019b) observed that the duration and moment of BB entrainment played a significant role in the effectiveness of the sessions. Carrier frequencies, gender and individual differences may further explain the potential differences in the study findings (Garcia-Argibay et al., 2019b; Reedijk et al., 2013). Future research may aim to explore the dominant frequency in different cognitive tasks. Neurological underpinnings may also be investigated to obtain an overall understanding of the various frequency waves associated with cognition. Investigating functional interplay between the brainwaves may further lead to a comprehensive understanding of the entrainment process. Additionally, since there are limited studies that have examined the practical effects of BB, more research is required to strengthen the estimation of the effect sizes.

Certain limitations exist in the meta-analysis data. For instance, a certain degree of publication bias may have influenced the analysis, although the statistical tests did not suggest its presence. However, we cannot completely rule out the possibility that including all non-significant studies that are not published could have resulted in smaller effect sizes. Moreover, since the inclusion criteria was limited to English language papers, there may be a possibility that the findings from the research papers that are written in other languages have not been taken into consideration. Detailed analysis in terms of the study's variables, like duration of entrainment, outcome variables, demographic details of the participants, and research designs, could have been significant in understanding the diverse frameworks used to examine the efficiency of BB entrainment on cognition, namely, memory and attention.

In conclusion, the results of the meta-analysis and findings from the supporting systematic review are promising and suggest a positive effect of BB entrainment on cognitive functions, in our case, memory and attention. Future research may validate the study's findings using larger samples and a standard framework to ensure replicability. Further, studies may also explore the guiding mechanism behind the efficiency of BB entrainment on cognitive functions in order to create a comprehensive understanding of the underlying process and its subsequent practical implications in society, such as clinical interventions and cognitive training programs.

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Conflict of interest The authors state that there is no conflict of interest.

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