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A parametric investigation of binaural beats for brain entrainment and enhancing sustained attention

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Binaural beats (BBs) have garnered attention as a highly accessible, noninvasive method to enhance cognitive performance, putatively via brain entrainment. However, the few studies that have directly examined the impact of BBs on sustained attention report inconsistent findings, perhaps due to wide variation in methodology. This study experimentally varied BB parameters while testing the effects of BBs on both sustained attention and brain entrainment. 80 undergraduate participants were randomized to 1 of 16 between-subject conditions in a 2 beats frequency (beta or gamma) × 2 carrier tone (340 or 400 Hz) × 2 onset time (before or with task onset) × 2 background masking noise (present or absent) factorial design. Participants completed a 2-visit within-subjects cross-over comparison of BBs vs. control auditory stimulation. EEG data were collected to validate brain entrainment. Gamma frequency BBs with a low carrier tone and white noise background improved general attention performance but did not reduce the vigilance decrement over time, suggesting BBs may modulate other cognitive aspects rather than sustained focus. EEG results confirmed brain entrainment, though entrainment varied with BB parameters and background noise. Further research should explore the interactions between BB parameters to optimize their use for cognitive enhancement.

Keywords Binaural beats, Sustained attention, EEG, Vigilance decrement, Cognitive enhancement, Brainwave entrainment

As the modern world grows increasingly complex and demanding, multiple scientific fields have shown interest in interventions for cognitive enhancement. One such intervention is binaural beats (BBs), an auditory stimulation technique that occurs when two tones of slightly different frequencies are presented dichotically. As the two sinusoidal tones interact in the auditory pathway, the result is amplitude modulation, a beat that varies at the frequency equal to the difference between the 2 tones[1,2]. Prior work suggests that BBs can enhance attention, memory, creativity, overall intelligence, and alleviate anxiety, pain perception, and stress[3]. Considering BBs' noninvasiveness and high accessibility (they require only headphones and internet access), they offer a promising tool for modulating cognitive functions.

Despite growing interest in using BBs for cognitive enhancement, few studies have directly examined the impact of BBs on sustained attention, or vigilance (we will use these terms interchangeably), the ability to maintain focus over a prolonged period of time[4,5]. Sustained attention is prototypically quantified as a vigilance decrement, or the degree to which performance declines over time[4], on long (often 30 + minutes[6]) monotonous tasks in which infrequent targets must be detected amid a stream of non-target stimuli[4,7,8]. Sustained attention plays a critical role in everyday life, including academic performance[9], driving[10] and occupations where a person must remain alert for unlikely, intermittent events[6].

While many studies have explored the impact of BBs on attention (see Table 1), only three studies (asterisked in Table 1) approximate the study of vigilance outlined above. Lane et al.[11] employed a 30-min continuous performance task with infrequent targets (10% of trials) and assessed the vigilance decrement. Robinson et al.[12] employed a 20-min psychomotor vigilance task, requiring participants to respond immediately when numbers began counting up on a screen. This task assessed vigilance via slowing reaction time as the task progressed. Finally, Vida et al.[13] employed a 20-min integrated visual and auditory continuous performance test (IVA-2 CPT); however, the frequency of target stimuli was unclear, and the vigilance decrement was not evaluated.

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Paper	Sample size	BB frequency	Carrier tone (Hz)	BB onset (relative to task)	Masking	Control condition	BB effect on attention	Task duration	Vigilance decrement assessment	Brain entrainment
Axelsen et al., 2020[51]	23 BBs	beta	172	before	none reported	No audio	BBs, experienced meditation > control, novice meditation	Not reported (~ 15 min)	NA	NA
	24 experienced meditation									
	22 novice meditation									
	21 control									
Cepeda-Zapata et al., 2023[52]	26	theta	~ 500	before	none reported	Theta BBs	Null effect	4.5 min	NA	NA
		beta								
Colzato et al., 2017[1]	18 BBs	gamma	340	before + during	white noise	Pure tone	BBs > control	Not reported (5–11 min)	NA	NA
	18 control									
Crespo et al., 2013[53]	20 commercial BBs	theta/beta	none reported	before	pink noise	Pink noise	Null effect	Not reported	NA	Null
	20 self-made BBs									
	20 control									
Engelbregt et al., 2019[54]	24	gamma	460	during	white noise	Gamma MBs, white noise	BB, MB > control on RT (not performance)	Not reported (~ 10 min)	NA	NA
Engelbregt et al., 2021[55]	25	gamma	460	during	none reported	Pink noise, MBs	BBs > pink noise > MBs	3.5 min	NA	Null
Hommel et al., 2016[21]	20 BBs	gamma	340	before + during	white noise	Pure tone	BBs > pure tone	Not reported (~ 5 min)	NA	NA
	20 control									
Kennel et al., 2010[56]	10 BBs	beta	none reported	during	pink noise	Pink noise	Null effect	Not reported	NA	NA
	10 control									
Kirk et al., 2019[57]	27 BBs	beta	172	before	none reported	No intervention	BBs, meditation > control	~ 7 min	NA	NA
	25 meditation									
	25 control									
*Lane et al., 1998[11]	29	beta	Mixed (100–300)	during	pink noise	Theta/delta BBs	Beta BBs > theta/delta BBs	30 min	Null	NA
		theta/delta								
Leistiko et al., 2023[58]	60	gamma	360	before + during	pink noise	Pure tone	Null effect	~ 8 min	NA	NA
Lim et al., 2018[59]	25	alpha/theta	300	before	music	Relaxation, massage	BBs + massage > massage, relaxation	15 min	NA	NA
Moessinger et al., 2021[60]	40 BBs	beta	400	before	music	Music	BBs > control	Not reported	NA	Positive
	40 control									
Reedjik et al., 2015[61]	24	alpha	340	before + during	white noise	Pure tone	Null effect	Not reported	NA	NA
		gamma					Gamma BBs > pure tone			
*Robison et al., 2021[12]	238 BBs	beta	208	during	none reported	Pure tone	Null effect	20 min	Null	NA
	250 control									
Ross & Lopez, 2020[62]	27	beta	440	during	none reported	No audio	Null effect	Not reported (~ 15 min)	NA	Positive
		gamma					Gamma BBs > no audio			
*Vida et al., 2023[13]	30	beta	408	before + during	none reported	Pure tone	BBs > control for auditory (not visual) sustained attention	20 min	NA	NA
Wang et al., 2022[35]	15 beta BBs	beta	247.5	before	none reported	Pure tone	Null effect	Not reported (< 10 min)	NA	NA
	15 relaxing music									
	15 gamma BBs	gamma	260							
	15 control									

Table 1. An overview of studies of binaural beats and attention, including sample sizes, control conditions, binaural beats parameters, and study findings. Papers marked with * had task duration of 10+ minutes. *BB* binaural beats, *NA* not assessed.

Two of the three studies[11,13] reported improvements in overall attention performance with beta BBs. However, neither of the two studies[11,12] that assessed performance over time found BBs to attenuate the vigilance decrement. Importantly, the simplicity of the tasks employed may have contributed to ceiling effects, limiting the potential for BBs to enhance vigilance[14,15]. For example, Robinson et al. [12] observed a small average vigilance decrement ($d = 0.27$), leaving little room for BBs to attenuate the vigilance decrement. The present study employs a more challenging vigilance task of longer duration (33 min), known for its ability to produce robust vigilance decrements and its sensitivity to interventions such as reinforcement, caffeine, and methylphenidate[7,16–18].

Although all three studies focused on beta BBs, they varied significantly in carrier tone frequency, the presence/absence of noise masking, and the timing of audio onset relative to the task (see Table 1). Thus, the mixed and somewhat disappointing results may be related to suboptimal parameter selection. Despite the large literature on BBs since Oster's seminal work in 1973[2], there remains a lack of direct investigation into the optimal creation and presentation methods for maximum cognitive benefit of BBs, representing a major gap in the literature. To fill this gap, we experimentally examined the impact of four BB parameters: BB frequency, carrier tone, masking, and BB onset time. First, BB frequency refers to the frequency of the beat after two tones are integrated, which should determine the frequency of brain entrainment. This frequency usually ranges from 4 to 40 Hz, roughly corresponding to the range of theta to gamma neuronal oscillations in the brain. Except for research on which cognitive states are related to specific brain frequencies, there is little guidance on which BB frequencies are optimal for cognitive performance improvement. Studies assessing attention and BBs have used a range of BB frequencies, including theta (7 Hz), alpha (10 Hz), beta (13-21 Hz), gamma (40 Hz), as well as combinations of frequencies (alpha/theta, theta/beta, theta/delta), with beta frequency and gamma frequency being the most common (see Table 1). Considering that beta and gamma brainwaves are correlated with alertness and focus[19], we compared the effects of gamma and beta BBs on vigilance (and EEG entrainment).

Second, carrier tone is the pitch perceived during BB exposure. It is a tone created through neural processing when the two separate frequencies are combined into one. The choice of carrier tone potentially affects the perception and effectiveness of BBs. One study[20] suggested that BBs are best perceived at 400 Hz. In the attention literature, carrier tones have ranged from 100 to 460 Hz (see Table 1). In the present study, we compared 340 and 400 Hz carrier tones based on our review of the literature (see Table 1).

Third, masking BBs involves adding background noise, which can be white noise, pink noise, music, or nature sounds. Consistent with evidence that noise enhances the perception of BBs[2], our review of the BB and attention literature (see Table 1) suggested that studies that use no masking tend to find null results while papers that add noise show improved attentional performance; white noise is the most commonly used[1,21]. Therefore, we compared white noise to no noise for this study to test whether white noise significantly improves BB effects. Importantly, when BBs included white noise masking, the control condition (no BBs) also included white noise, thereby preventing confounding of white noise with BBs.

Fourth, BB onset time refers to when exposure to BBs begins and ends in relation to the task, which can be before and/or during the task. Studies that expose participants to BBs before and during the task tend to show behavioral improvement. Conversely, despite being common choices, exposure to BBs only before or during the task resulted in no effects on behavior (see Table 1). Considering the most common choices in the literature are during and before + during[1,11–13], we compared these conditions in this study.

A final critical limitation in the literature on BBs and attention is the lack of physiological confirmation of brain entrainment. Since the two tones that create BBs are played into each ear separately, each tone produces a phase-preserved impulse that reaches the medial superior olivary nucleus (MSO) in the brainstem, the first auditory center that receives bilateral signals and the location in which beat perception originates[2,22–24]. A combined signal from MSO is sent to the inferior colliculus, from which it spreads throughout the brain[25]. BBs are theorized to induce brainwave entrainment, a frequency following response (FFR) of neuronal oscillations that matches the frequency of the rhythm of the perceived beat[26]. In other words, neuronal oscillations are phase-locked to the rhythmic stimulus, and this can be quantified as an increase in electroencephalogram (EEG) signal power (amplitude) of a specified frequency assessed via frequency domain analysis. Although studies on brain entrainment following BB stimulation have variable outcomes, several studies found evidence that BBs entrain the EEG[27]. Indeed, because different EEG frequencies are associated with different functional states[28,29], BB entrainment is the theorized mechanism by which BBs modulate those states. Confirming brain entrainment to the BB frequency is an important manipulation check and essential for evaluating the mechanism by which BBs exert their cognitive effects. However, most previous studies on BBs and attention either did not collect EEG or did not assess FFR (shown as "NA" in Table 1) and none of the three studies that assessed vigilance did so (asterisked studies in Table 1). We addressed this limitation by collecting EEG for the duration of the task and performing FFR analysis to evaluate brain entrainment at the corresponding BB frequencies (16 Hz/beta, 40 Hz/gamma).

In sum, we tested the hypothesis that BBs enhance sustained attention using a robust vigilance task by comparing BBs to control audio in a multi-session crossover (within-subjects) design. We also randomized participants to different levels of four BB parameters to understand the optimal conditions for enhancing attention with BBs. Finally, we tested the hypothesis that BBs would result in EEG entrainment and evaluated whether entrainment was influenced by BB parameters.

Results

As detailed in Methods, 80 undergraduate participants were randomized to 1 of 16 between-subject conditions in a 2 beats frequency (beta or gamma) × 2 carrier tone (340 or 400 Hz) × 2 onset time (before or with task onset) × 2 background masking noise (present or absent) factorial design. All participants completed a 2-visit within-subjects cross-over comparison of BBs vs. control auditory stimulation. Each session included the Identical Pairs Continuous Performance Task (IP-CPT) during which EEG was recorded. The primary IP-CPT outcome was percent hits (correct target detections) across 12 trial blocks. EEG data were analyzed to assess brain entrainment, calculated as the signal-to-noise ratio of EEG power density at the target beta and gamma frequencies. Pre/post subjective assessments of mood (Profile of Mood States) and ratings of the auditory stimulation were collected.

Identical pairs continuous performance task (IP-CPT) performance

Consistent with a vigilance decrement, percent hits robustly declined across trial blocks (block linear: $F(1,53) = 112.550$, $p < 0.001$, $\eta_p^2 = 0.68$; block quadratic: $F(1,53) = 32.972$, $p < 0.001$, $\eta_p^2 = 0.384$; see Fig. 1). However, contrary to our hypothesis, BBs did not, on average, attenuate the vigilance decrement (Treatment Condition × Block linear and Block quadratic $Fs(1,53) = 0.1$ and 0.38, $ps = 0.751$ and 0.540, respectively). There was a significant interaction of treatment condition and duration on the linear vigilance decrement across blocks ($F(1,53) = 5.569$, $p = 0.022$, $\eta_p^2 = 0.095$). Follow-up tests in each duration condition suggested that the linear vigilance decrement was attenuated during BBs compared to pure tone for participants who received audio stimulation before and during the IP-CPT (Condition × Block linear $F(1,26) = 4.8$, $p = 0.038$, $\eta_p^2 = 0.16$), but not for participants who received audio stimulation only during the task (where the effect was non-significantly reversed; Condition × Block Linear $F(1,24) = 3.0$, $p = 0.096$; see Fig. 1, which presents average percent hits for all Treatment Condition (binaural beats vs. pure tone) × Trial Block (12) × Audio onset Time (with vs before task) conditions; data in the figure are averaged across levels of beats frequency, carrier tone, and white noise presence). However, even among participants who received audio stimulation before and during the IP-CPT, performance did not significantly differ between BBs and pure tone in any trial block (all $ps > 0.10$). No other BB parameters interacted with block (all $Fs < 1.96$, all $ps > 0.17$).

Though BBs did not robustly affect the vigilance decrement across blocks, there was evidence that BBs influenced target detection averaged across trial blocks. Specifically, as can be seen in Fig. 2, average percent hits were greater during BBs compared to pure tone among people who received gamma beats with the low (340 Hz) carrier tone ($p = 0.002$), but not for people who received gamma beats with the high (400 Hz) carrier tone ($p = 0.76$ in the opposite direction) or those who received beta beats with either the low or high carrier tone ($ps = 0.13$ – in the opposite direction – and 0.46, respectively; Beat Frequency × Carrier Frequency × Treatment, $F(1,53) = 8.5$, $p = 0.005$, $\eta_p^2 = 0.138$; Beat Frequency × Treatment, $F(1,53) = 3.7$, $p = 0.058$; overall Treatment Condition $F(1,53) = 0.8$, $p = 0.385$).

As can be seen in Fig. 3, average percent hits were also greater during BBs compared to pure tone among people who had white noise in the background ($p = 0.033$) but not for people who did not have background noise ($p = 0.434$ in the opposite direction; Noise × Treatment, $F(1,53) = 4.2$, $p = 0.047$, $\eta_p^2 = 0.073$). The influence of BBs and background noise on percent hits tended to further interact with auditory stimulation duration, Noise × Duration × Treatment ($F(1,53) = 3.4$, $p = 0.07$). Specifically, average percent hits was greater in the BBs condition compared to pure tone only when white noise was present and the auditory stimulus began playing with the task ($p = 0.013$), not in white noise/auditory stimulus before the task ($p = 0.602$), no white noise/auditory stimulus began with the task ($p = 0.191$), or no white noise/auditory stimulus began before the task ($p = 0.774$; see Fig. 3).

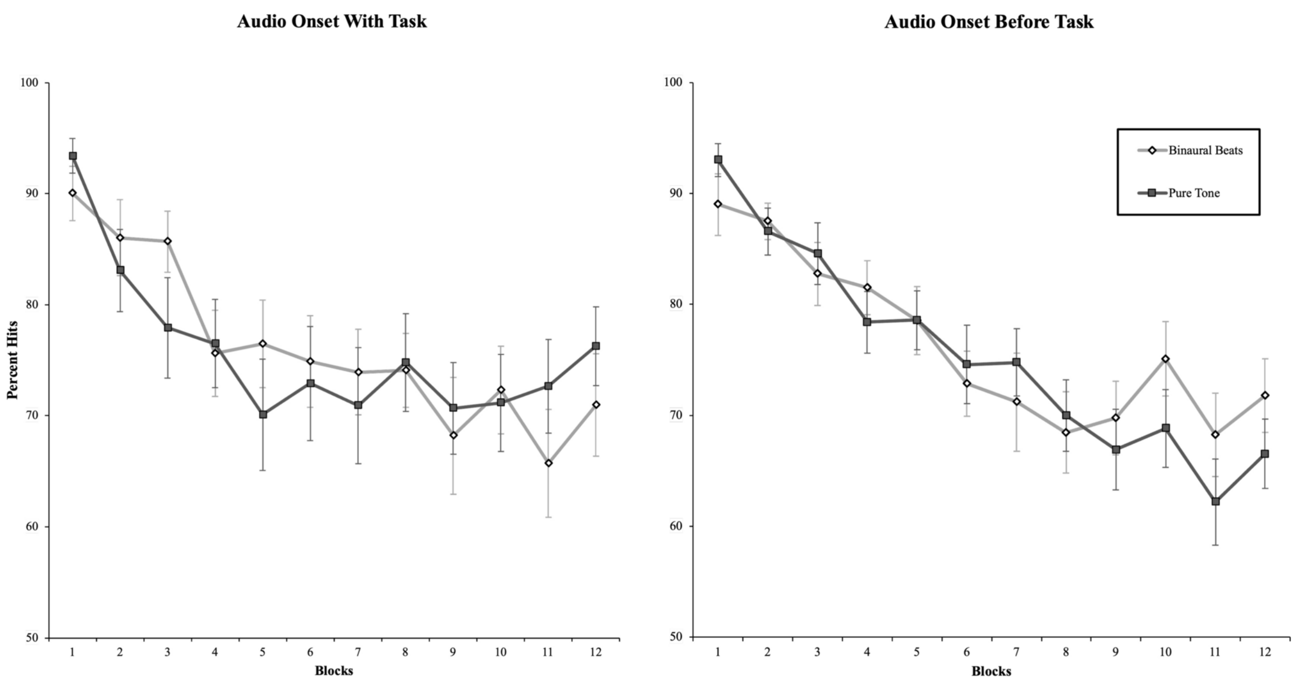

Fig. 1. Average percent hits in the IP-CPT for all treatment condition (binaural beats vs. pure tone) × trial block (12) × audio onset time (with vs before task) conditions (data are averaged across levels of beats frequency, carrier tone, and white noise presence). Linear vigilance decrement was attenuated during BB compared to pure tone for participants whose audio onset was before the task but not for participants who received audio stimulation only during the task. Bars are standard errors.

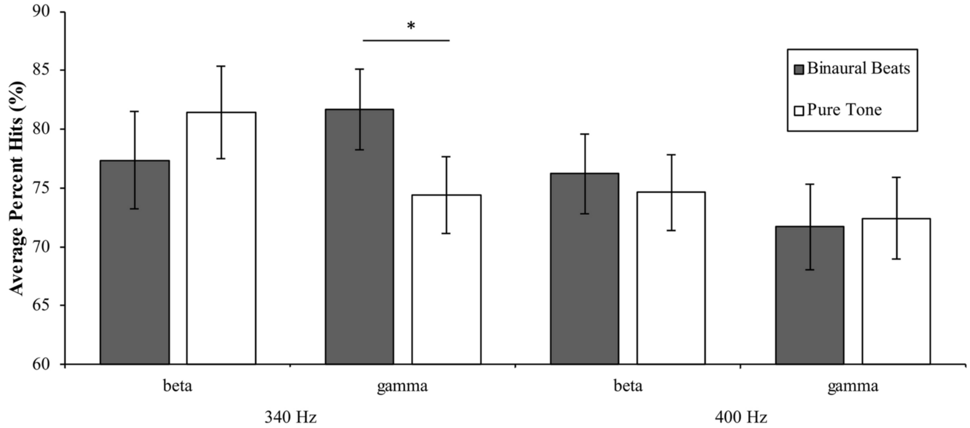

Fig. 2. Average percent hits in the IP-CPT for all treatment condition (binaural beats vs. pure tone) × beats frequency (beta vs. gamma) × carrier frequency (340 Hz vs. 400 Hz) conditions (data are averaged across levels of audio onset and white noise presence). Gamma beats with 340 Hz carrier tone improved average IP-CPT performance compared to pure tone control. Bars are standard deviations, *p = 0.002.

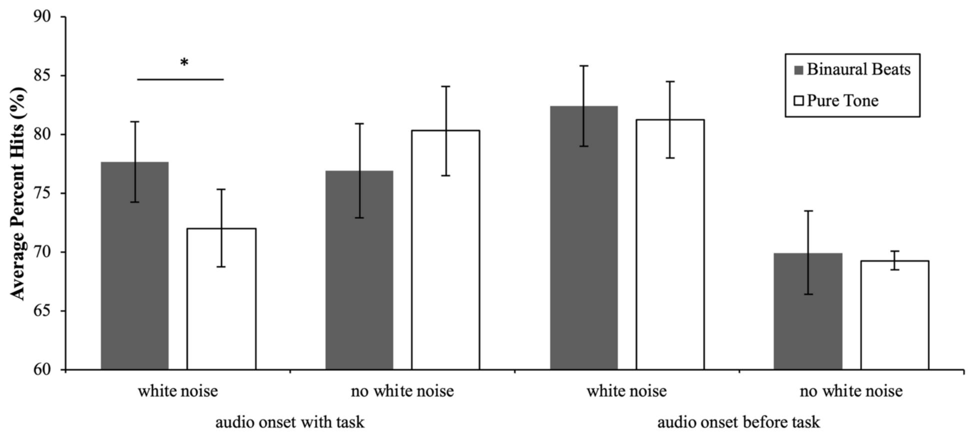

Fig. 3. Average percent hits in the IP-CPT for all treatment condition (binaural beats vs. pure tone) × Masking (white noise vs no white noise) × Audio Onset Time (with vs. before task) conditions (data are averaged across levels of beats frequency and carrier tone). Audio onset with task while white noise was present improved average IP-CPT performance in the binaural beats group compared to pure tone control. Bars are standard errors, *p = 0.013.

The impact of BBs on percent hits did not significantly vary as a function of carrier tone, duration, or interactions not mentioned above (all $Fs < 0.813$, $ps > 0.37$). False alarm rates were low (all means < 2%) and did not significantly differ between BBs and control or as a function of BB parameters (all $Fs < 3.038$, $ps > 0.09$).

EEG power density (brain entrainment)

Consistent with entrainment, noise-corrected EEG power density (PD S2N) at the beta beats frequency (16 Hz) was greater during BBs compared to pure tone for people who received beta beats ($p = 0.001$) but not people who received gamma beats ($p = 0.856$); conversely, S2N PD at the gamma beats frequency (40 Hz) was greater during BBs compared to pure tone for people who received gamma beats ($p < 0.001$) but not beta beats ($p = 0.158$); EEG Frequency × Beat Frequency × Treatment, $F(1,52) = 25.9$, $p < 0.001$, η_p^2=0.33). As can be seen in Fig. 4, this effect was moderated by the presence of background noise (Noise × EEG Frequency × Beat Frequency x Treatment, $F(1,52) = 5.126$, $p = 0.028$, η_p^2=0.09). Specifically, white noise attenuated the entrainment, but this effect was larger for gamma BBs (gamma S2N PD during gamma beats compared to pure tone; $p < 0.001$ without white noise vs $p = 0.04$ with white noise) than for beta BBs ($p = 0.029$ with white noise; $p = 0.017$ without white noise). Overall, brain entrainment occurred in every condition but was particularly pronounced in participants who received gamma BBs and when beats were not masked by white noise.

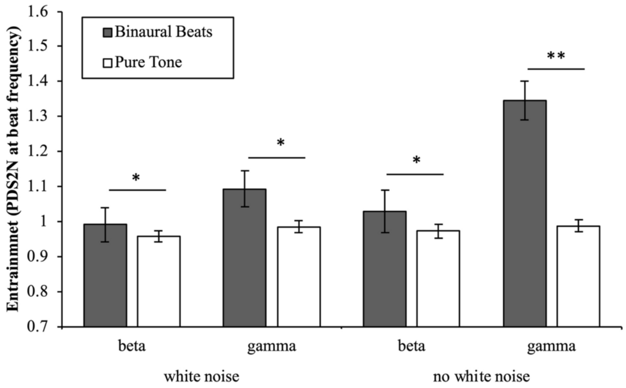

Fig. 4. Average signal-to-noise ratio of power density for all treatment condition (binaural beats vs. pure tone) × beats frequency (betas vs gamma) × masking (white noise vs no white noise) conditions (data are averaged across levels of carrier tone and audio onset). For the beta beats group, power density signal-to-noise ratio (PDS2N) was calculated at ~ 16 Hz; for the gamma beats group, PDS2N was calculated at ~ 40 Hz. Each bar thus reflects PDS2N values specifically at the frequency corresponding to that group's binaural beat condition. Brain entrainment was stronger in the absence of white noise, especially for gamma binaural beats. Bars are standard errors, *p < 0.05, **p < 0.001.

Self-report scales

Profile of mood states (POMS)

POMS data were collected in order to assess self-reported fatigue levels pre and post IP-CPT. Consistent with the expected effects of the vigilance task, the scores on 3 fatigue-related scales (selected a priori) declined from pre- to post-task assessment (fatigue-inertia scale pre-post $F(1,48) = 33.6$, $p < 0.001$, η_p^2=0.41; vigor-activity scale pre-post $F(1,48) = 58.5$, $p < 0.001$, η_p^2=0.55; confusion-bewilderment scale pre-post $F(1,48) = 1$, $p = 0.035$, η_p^2=0.09). Pre-post changes in POMS scales did not significantly vary as a function of BBs or any of the auditory stimulus parameters (all $Fs < 3.596$, $ps > 0.064$).

Audio rating scales

Self-reported pleasantness and perceived impact of the auditory stimulus on performance did not differ between binaural beats and control (all $Fs(1,53) < 3.029$, all $ps > 0.08$).

Discussion

The literature on binaural beats (BBs) and sustained attention is mixed, potentially because of limited statistical power and/or variability in the BB methods employed. The present study sought to advance the field in both respects by using a vigilance task sensitive to other treatment effects and systematically comparing the role of several key parameters of BB stimulation. Although there was a robust vigilance decrement in task performance (η_p^2=0.68) and our sample size provided sufficient statistical power, there was minimal evidence that BBs improved sustained attention (i.e., attenuated the vigilance decrement). However, general attention performance across the entire task was improved for specific BB parameters (i.e., gamma frequency (40 Hz) beats with a low (340 Hz) carrier tone; BBs with background white noise). This study was also relatively novel in the attention literature for performing a manipulation check – whether BBs led to brain entrainment, the leading hypothesized mechanism by which BBs are thought to exert their effects on psychological processes. We found that BBs did elicit significant entrainment at their specific frequency (i.e., an increase at 16 Hz for beta beats and 40 Hz for gamma beats). Entrainment was stronger for gamma beats, which aligns with the findings that gamma beats had stronger behavioral effects than beta beats. However, while white noise aided the effects of BBs on attention, brain entrainment was weaker in the presence of white noise. Below, we discuss the interpretation of these effects in the context of prior work and future directions.

The observed pattern of improved overall performance but unaffected vigilance decline necessitates an examination of attention subdivisions. In the literature, attention is categorized into three subtypes: alerting, orienting, and executive[30]. Sustained attention, associated with tonic alerting attention, is regulated by arousal systems via the locus coeruleus[31]. Although the precise mechanisms by which BBs influence cognition remain unclear, it is hypothesized that BBs align cortical brain oscillations with BB frequencies. This entrainment may not impact subcortical structures like the locus coeruleus, leaving sustained attention unaffected. Our findings are generally consistent with previous studies of BBs and sustained attention; two of three studies with longer-duration (20 + minutes) sustained attention tasks found BBs enhanced average performance[11,13], but neither study that assessed vigilance over time observed improvements in vigilance with BBs[11,12] (see Table 1). Improvement in general performance could be explained by BB effects on the other 2 attention subtypes: orienting and executive. Orienting attention refers to our ability to prioritize behaviorally relevant sensory input while ignoring distracting stimuli. BB stimulation may enhance this selection process, improving focus on presented stimuli (e.g., numbers on a screen) and thus overall performance. Synchronization in gamma frequencies in neurons representing attended stimulus leads to increased processing of that stimulus, while beta frequency synchronization is associated with reduced visuospatial attention[32]. Our study found that gamma BBs, rather than beta BBs, improved overall performance, which is broadly consistent with the hypothesis that BBs influence orienting attention.

The observed improvement in average attentional performance might also stem from enhancements in executive attention, which involves maintaining task-relevant goals. Brain oscillatory activity associated with executive attention exhibits a complex pattern. For instance, executive control involves an interplay between gamma and theta oscillations in the prefrontal cortex[33]. It is plausible that gamma BBs enhanced executive attention due to their role in executive functioning. One study investigating the effects of gamma and beta BBs on the attentional blink paradigm—a task closely linked to cognitive control and executive attention—found that while both groups showed improvement across sessions, gamma BBs led to greater performance gains between sessions[62].

Other cognitive functions also warrant consideration. For instance, gamma oscillations have been linked to working memory performance[34]. The IP-CPT task includes a working memory component in that the preceding number must be retained and compared to the current number. Gamma frequency brain entrainment might have enhanced working memory performance, thereby improving overall task performance. However, given the minimal working memory demands of this task, this explanation is less likely. The literature on working memory and gamma BBs presents mixed findings; while two studies reported improved working memory performance compared to a pink noise control group[35] or pre/post stimulation[67], another found no significant effects[36], making it unclear whether gamma beats can influence working memory performance. Other studies have shown that BBs in the alpha[37,38] and theta[39] frequency ranges can enhance working memory performance.

An essential aspect of this study was the parametric approach; we experimentally varied four characteristics of the auditory stimulation to understand the degree to which they impacted the effects of BBs on attention. This approach is crucial for relating the present work to prior work and for establishing an optimal methodology for BB stimulation to improve attention. Our findings indicate that a lower carrier tone (340 Hz) significantly improved average performance, particularly in the gamma BB groups, whereas BBs centered at a higher carrier (400 Hz) tone did not improve attention.

In the context of prior work on BBs and sustained attention, two of the three previous studies used a lower carrier tone[11,12] and reported mixed results. Consistent with the present findings, one of those studies[12] (208 Hz carrier tone) found no effect with beta BBs. The other study[11] (combination of 100, 200, 250, and 300 Hz carrier tone) reported improved performance with beta beats compared to theta/delta beats. However, they did not compare these effects to a no-BB group, complicating interpretation, as theta/delta BBs may have decreased sustained attention performance. That is, theta/delta beats may have disrupted attention. In contrast to the present results, Vida et al.[13] employed a higher carrier tone (408 Hz) and found beta BBs to increase average performance compared to a pure tone control. It is also worth noting that carrier tone had no significant effect on brain entrainment in the present study, suggesting that any impact of carrier tone on attention may be mediated through an alternative mechanism. However, because none of the prior BB-vigilance studies included data on entrainment, firm conclusions about whether gamma BBs with a low carrier tone is a particularly effective combination for enhancing overall attention requires replication.

White noise masking may be another important BB parameter. Our study found that BBs improved attention in the presence of background white noise, but not in the absence of white noise. This finding is broadly consistent with some prior findings, where one study[12] did not report masking and observed no beneficial effect of BBs, and another[11] reported positive effects with pink noise masking. However, another study[13] found that BBs improved average performance in the absence of masking noise. Similarly, we observed that gamma beats with a low carrier tone improved performance regardless of white noise. Thus, it appears that noise masking may improve the impact of BBs under some conditions but is not essential for the effectiveness of BBs. Interestingly, in our study, white noise interfered with brain entrainment, especially for the gamma beats group. One potential explanation is gamma-to-beta transition in response to white noise (we thank an anonymous reviewer for suggesting this hypothesis)[66]. However, for the gamma beats group that received white noise, entrainment (PDS2N) at the beta frequency did not differ significantly between the BB and control conditions ($p = 0.28$). PDS2N was also lower at the beta frequency than at the gamma frequency (0.93 [0.88] for beta vs. mean [SE] = 1.09 [0.05] for gamma). An alternative explanation is that white noise interfered with or masked the beat frequency, reducing the level of entrainment. Previous research indicates that noise hinders auditory neural encoding[65]. In other words, white noise diminished entrainment for both BB frequencies, but interference might have been larger for gamma than beta BBs due to the 1/f nature of EEG power signal; that is, higher frequencies like gamma have lower power and are more susceptible to noise[28].

Although the presence of white noise interfered with brain entrainment, it improved general attention performance, suggesting that white noise may enhance general attention through a different mechanism. For example, one study[40] found that white noise improved sustained attention performance towards the end of a test in children with ADHD compared to no audio, suggesting that white noise alone can be an effective tool for improving attention.

We also examined the impact of whether audio stimulation began before task onset or occurred simultaneously with task onset. We found modest evidence that starting BBs 10 min before the task attenuated the linear vigilance decline. However, performance did not significantly differ between BBs and control in any trial block (see Fig. 1). Additionally, audio onset interacted with white noise, such that average performance was significantly better in the BB group when white noise was present, and BBs started playing with the task. The timing of audio onset did not affect brain entrainment. We tentatively interpret these mixed results to suggest that the duration of audio stimulation does not play a strong role in BB effectiveness.

There are several limitations in this study. First, although the sample size of 64 was relatively large for this literature, it was too small to allow us to evaluate the highest-order interactions of BB parameters with treatment

Baseline characteristic	Total	Binaural beats frequency		Carrier tone frequency		Auditory stimulus onset		Masking/background noise	
	Sample (*n* = 64)	Beta (*n* = 32)	Gamma (*n* = 32)	340 Hz (*n* = 31)	400 Hz (*n* = 33)	Before task (*n* = 33)	With task (*n* = 31)	White noise (*n* = 34)	None (*n* = 30)
Age (mean, SD)	19.0 (1.1)	18.9 (1.0)	19.1 (1.2)	18.9 (0.9)	19.0 (1.3)	19.3 (1.3)	18.6 (0.7)	18.9 (1.0)	19.1 (1.3)
Sex (n, %)									
Female	26 (40.6)	13 (40.6)	13 (40.6)	15 (48.4)	11 (33.3)	14 (42.4)	12 (38.7)	9 (26.5)	17 (56.7)
Race (n, %)									
Asian	12 (18.8)	7 (21.9)	5 (15.6)	6 (19.4)	6 (18.2)	9 (27.3)	3 (9.7)	7 (20.6)	5 (16.7)
Black/African American	10 (15.6)	3 (9.4)	7 (21.9)	7 (22.6)	3 (9.1)	7 (21.2)	3 (9.7)	4 (11.8)	6 (20.0)
White/Caucasian	39 (60.9)	20 (62.5)	19 (59.4)	17 (54.8)	22 (66.7)	15 (45.5)	24 (77.4)	21 (61.8)	18 (60.0)
Other/prefer not to answer	3 (4.7)	2 (6.3)	1 (3.1)	1 (3.2)	2 (6.1)	2 (6.1)	1 (3.2)	2 (5.9)	1 (3.3)
Hispanic/Latino (n, %)	6 (9.4)	2 (6.3)	4 (12.5)	2 (6.5)	4 (12.1)	3 (9.1)	3 (9.7)	3 (8.8)	3 (10.0)

Table 2. Participant characteristics for the overall sample and for each level of the four binaural beats parameters.

condition, as there were only ~ 8 participants in each of the smallest cells of the design. Replication of our initial parametric investigation in an even larger sample would strengthen our understanding of the conditions under which BBs are most helpful for improving attention – and other cognitive functions. Second, while we chose a pure tone as an active control condition to help isolate the unique effects of BBs beyond simple auditory stimulation—an approach employed by other methodologically strong papers in the literature[1,12,13,21,35,58,61]. Although using an active control may be seen as a methodological strength that increases internal validity by ensuring that any observed effects are not merely due to the presence of any sound, this design choice also has limitations. That is, incorporating a no-sound (passive) control condition could offer a more naturalistic comparison scenario and might better reflect real-world environments where individuals study or work in silence. However, it is challenging to incorporate both types of controls in a single study, and given the aims of this investigation, we believe that employing an active control aligns with current methodological standards and provides a clearer test of the unique contribution of BBs. Third, the BBs in this controlled investigation generalize well to the scientific literature but may not adequately represent the BBs commonly available in the real world. For example, BB audios available on Spotify or YouTube typically have very low carrier tones. In addition, in natural environments, people select their own listening volume, whereas in this study volume was set to 70 dB. This might be why participants found both BB and pure tone audios to be somewhat unpleasant, which might have attenuated the beneficial effects of BBs. Future parametric work should consider very low carrier tone frequencies and manipulate tone volume (including a condition in which participants can individually tailor volume). Finally, we examined a convenience sample of college students, which further limits generalizability.

This study was the first to systematically examine the impact of multiple BB parameters on the impact of BBs on attention. Despite employing a classic sustained attention paradigm and a relatively large sample, BBs had a modest impact on the vigilance decrement. However, gamma beats with low carrier tone and beats masked with white noise (regardless of beat frequency) appeared to be the best combinations for enhancing overall attention performance. Gamma BBs also led to greater brain entrainment than did beta beats, but the impact of white noise on entrainment was opposite the behavioral effects. To better understand the precise effects of BBs, future studies should examine additional types of attention, as well as working memory, while concurrently assessing entrainment and other candidate physiological mechanisms. To optimize the utility of BBs, future work should build on the parametric approach taken in the present study and aim to increase the generalizability of their findings, including the use of community samples and explicit evaluation of the degree to which BB effects on cognition predict improved performance in real-world settings (e.g., studying[9] or driving).

Methods

This study was preregistered at Open Science Framework[64].

Participants

80 University at Buffalo undergraduates taking introductory psychology participated in exchange for course credit. All participants reported normal or corrected-to-normal vision and hearing and fluency in English. Of these 80, 12 did not complete the second session and were excluded. Another 4 participants performed ≥ 2 standard deviations below the mean percent hits on the attention task in one or both sessions and were excluded, leaving a final sample of 64 participants with a mean age of 19 years. Exclusions were generally balanced across two levels of each auditory stimulation parameter (i.e., 50% were in the beta beats group, 31% in the high carrier tone group, 38% in the white noise present group, and 50% in the audio onset with task group). Detailed participant characteristics are presented in Table 2. Consistent with random assignment, participant characteristics were consistent across most BBs parameter conditions except for sex imbalances across background noise conditions and race imbalances across auditory stimulus onset conditions (see Supplemental Analyses).

Study design

The study employed a 2 Beats Frequency × 2 Carrier Tone × 2 Auditory Stimulus Onset × 2 White Noise × 2 Binaural Beats (present vs. absent/pure tone) factorial design. BBs was a repeated measures factor with BBs present in one lab visit and absent in the other. All other factors, the 4 BB parameters, were between-subjects factors. All condition assignments were randomized at the beginning of Session 1 according to a pre-determined, counterbalanced list.

Procedures

The study was conducted in accordance with the ethical principles of the Declaration of Helsinki, and all procedures were approved by the University at Buffalo Institutional Review Board. Participants attended two 2-h sessions ~ 1 week apart (mean = 7 days; SD = 1.4 days). Participants provided informed consent at the beginning of Session 1 and were informed that the purpose of the study was to examine the effects of different sounds on sustained attention. The presence of BBs was not described until participation was complete. Other than consent, the demographics questionnaire (Session 1), participant debriefing (Session 2), the type of auditory stimuli presented (BBs or pure tone, order randomized across participants), the sessions were identical.

During each session, participants entered a sound-attenuated chamber and completed the Profile of Mood States (POMS)[41]. Next, a research assistant set up the EEG (see Electrophysiological measures*)*. Once the EEG signal quality was confirmed, headphones were placed on the participant. During the next 10 min, participants completed several supplemental questionnaires (data not reported) and a practice version of the Identical Pairs Continuous Performance Task (IP-CPT)[42]. Next, participants engaged in the full IP-CPT (described below). Depending on a participant's random assignment, the auditory stimulus (BBs or pure tone) began playing at the beginning of the 10-min pre-task period or at the beginning of the task. Once started, the auditory stimulus played continuously throughout the duration of the IP-CPT. After the task, participants completed POMS again and rated their experience with the auditory stimulus (pleasantness-unpleasantness; perception of how it affected their performance).

Identical pairs continuous performance task (IP-CPT)

CPTs require sustained attention to a monotonous stream of stimuli with rare targets[43]. To avoid ceiling effects[15], an identical pairs CPT was modestly adapted from prior work[7,44,45]. Participants viewed a series of 4-digit numbers and were instructed to press the space bar when the stimulus was identical to the one immediately preceding it, which occurred on 10% of trials. Numbers were presented in one of 4 randomly assigned orders.

All participants completed 28 practice trials at a slow pace (600-ms stimulus duration; 2,000-ms response window) and correctly detected at least two of the three targets with no more than one false alarm to nontargets. The main task consisted of 1200 trials in which each trial had a 150-ms stimulus presentation and a 1500-ms interstimulus interval/response window (~ 36 stimuli/minute). The total duration of the task was ~ 33 min. The IP-CPT was programmed using E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA).

Auditory stimulation, including binaural beats

Participants were presented with auditory stimulation containing BBs during one session and a pure tone (matched to the BBs carrier tone, white noise condition, and auditory stimulus onset condition) during the other session. As described above, the nature of the BBs condition systematically combined 4 parameters: gamma or beta beats, 340 or 400 Hz carrier tone, auditory stimulus onset 10 min before or at the beginning of the task, and presence or absence of white noise. Auditory stimuli were created in Audacity® software[46]. BBs were created by generating 2 simple waveforms either equidistant from the 340 Hz or 400 Hz carrier tone (e.g., 332 Hz + 348 Hz to produce beta beats at the 340-Hz carrier tone). The lower frequency was always played into the left ear, and the tones to each ear at 70 dB(A). Binaural white noise was 60 dB(A).

EEG methods

EEG recordings were made using a 32-channel Active Two BioSemi system (BioSemi, Amsterdam, Netherlands). Only EEG at the Cz electrode was analyzed, considering its location above the auditory cortex, allowing it to pick up auditory signals[63]. A mesh electrode cap was positioned corresponding to the international 10/20 system. Non-invasive pin electrodes were inserted into pre-gelled electrode holders in the cap. Four additional Ag/AgCl flat electrodes were placed on the right and left mastoids (for EEG reference) and above and below the right eye aligned with the pupil for a vertical electrooculogram (EOG; for eyeblink correction). Both EEG and flat electrode signals were preamplified by the BioSemi ActiveTwo system and sampled at 512 Hz.

Offline, EEG data for the 33-min task were reduced with BrainVision Analyzer (BVA) Version 2.2 (Brain Products GmbH, Gilching, Germany)[47]. All channels were re-referenced to the average of mastoids and bandpass (1–50 Hz) and notch (60 Hz) filtered. Eye movement artifacts were removed from EEG using the Gratton & Coles blink detection algorithm[48] using vertical EOG. Data were then subdivided into 2-s epochs. Epochs that met any of the following criteria were eliminated: voltage step greater than 30 μV between samples, voltage difference of 200 μV within a 200 ms interval, and voltage difference of less than 0.5 μV within 100 ms intervals. On average, 96.7% (SD = 5.6%) of segments were retained per participant. Epochs were subjected to a Fast Fourier Transform[49] with 0.5-Hz resolution and 10% Hanning windows. Magnitude was calculated as power density (μV2/Hz) averaged across all epochs within subjects and sessions. To evaluate whether BBs elicited a frequency-following response (brain entrainment), response magnitude at 16 Hz (corresponding to beta beats) and 40 Hz (corresponding to gamma beats) was calculated. Mean power density (PD) was calculated for beta (15.5–16.5 Hz) and gamma (39.5–40.5 Hz) frequencies, as well as 3 0.5-Hz steps above and below those windows for calculation of signal-to-noise (S2N) ratio:

$$betaPDS2N = \frac{meanPD(15.5{,}16{,}16.5Hz)}{(meanPD(14{,}14.5{,}15.5Hz) + meanPD(17{,}17.5{,}18Hz))/2}$$

$$gammaPDS2N = \frac{meanPD(39.5{,}40{,}40.5Hz)}{(meanPD(38{,}38.5{,}39Hz) + meanPD(41{,}41.5{,}42Hz))/2}$$

Profile of mood states (POMS)[41].

POMS data were collected via REDCap[50] in order to assess self-reported fatigue levels pre and post IP-CPT. The POMS is a widely used, 65-item checklist of feelings, with each item rated on a 5-point Likert scale (from 0 = 'Not at all' to 4 = 'Extremely'). Participants were asked to report how they are feeling in the moment ('right now'). Though the POMS has 6 subscales, we focused a priori on three: vigor/activity, fatigue/inertia, confusion/bewilderment.

Statistical analysis

All analyses were conducted via IBM SPSS Statistics for Macintosh, Version 28.0. For all analyses, two-tailed alpha of 0.05 was used to evaluate statistical significance. Significant interactions were further examined with simple effects and pairwise comparisons.

As in prior work[7,45], the primary outcome was IP-CPT percent hits (number of targets detected/total number of targets *100). Secondary outcomes included percent false alarms (to ensure that any improvements in detection of targets were not due to an increase in overall response rate), EEG noise-corrected power density (PD S2N at each beat frequency, 16 and 40 Hz), and POMS self-report fatigue/inertia, confusion/bewilderment, and activity/vigor scores.

All outcomes were analyzed using repeated-measures analysis of variance (ANOVA) with beats condition (present or absent) as a within-subjects factor and the 4 auditory stimulation parameters (gamma vs beta beat frequency, 340 or 400 Hz carrier tone, presence or absence of white noise, auditory stimulus onset before or during the task) as between-subjects factors. To examine changes in performance across time (i.e., the vigilance decrement), percent hits were calculated within-participant for the twelve 100-trial blocks. Effects of trial block were evaluated using linear and quadratic trends across blocks. For the POMS self-report analysis, pre- vs. post-task response was an additional within-subjects factor. Randomizing participants into a combination of four BB parameters (2 beats frequency × 2 carrier tone × 2 onset time × 2 background masking noise) yielded 16 between-subjects cells of the design, with an average of 4 participants in each cell (SD = 0.8, range = 2–6). Given the small cell sizes for higher-order interactions, we did not test interactions involving more than two between-subjects factors (with ~ 16 participants in each of the 2 × 2 cells). For all outcomes, we were focused on effects involving treatment condition (beats vs. control); interactions that did not involve treatment condition are generally not discussed. Visual inspection of histograms and Q-Q plots suggested that the critical differences between BBs and control conditions were approximately normally distributed (e.g., for percent hits the difference score was modestly positively skewed); given ANOVA's robustness to violations of the normality assumption, this statistical approach was considered appropriate.

Data availability

The data recorded for this study will be made available upon reasonable request to the first author, Anastasiia Melnichuk (email: amelnich@utexas.edu).

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Author contributions
All authors had significant contributions to the manuscript. All authors have read and approved the final manuscript. A.M. was the main investigator and led all parts of the project, including conceptualization, methodology, data collection, analysis, and manuscript preparation. L.W.H. Jr. served as the principal investigator in the lab where the project was conducted, significantly contributing to conceptualization, methodology, data analysis, and providing feedback on manuscript drafts. R.K.C. contributed to conceptualization, methodology, data collection, data analysis, and provided feedback on the manuscript.

Competing interests
The authors declare no competing interests.

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