

Metadata of the chapter that will be visualized in SpringerLink

Book Title	Recent Challenges in Intelligent information and Database Systems	
Series Title		
Chapter Title	FOCUS +: Enhancing Sustained Attention Through Comparative Evaluation of Digital and Physical Interventions	
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Abstract	Sustained attention is critical for success in work, education, and daily life, yet maintaining prolonged focus remains challenging. To address this, various interventions such as meditation, cognitive training, and auditory stimulation have been proposed. However, the comparative effectiveness of these interventions in improving sustained attention in Human-Computer Interaction (HCI) remains underexplored. This study investigates and constructs the efficacy of three widely used attention-enhancing techniques: binaural beats, cognitive training, and mindfulness meditation. Forty participants were assessed using continuous performance tests (CPTs) before and after undergoing one of the interventions. Our findings indicate that cognitive training had the most effect on improving attentional performance (mean difference = 0.06, $t = 3.16$, $p < 0.05$). These results highlight the effectiveness of interventions that actively engage working memory and cognitive control. We provide practical implications and design guidelines	

for HCI researchers and practitioners developing interactive systems aimed at supporting and improving sustained attention.

Keywords (separated by '-')	sustained attention - EEG brainwave - continuous performance test - binaural beats - cognitive training - meditation
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FOCUS +: Enhancing Sustained Attention Through Comparative Evaluation of Digital and Physical Interventions

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Abstract. Sustained attention is critical for success in work, education, and daily life, yet maintaining prolonged focus remains challenging. To address this, various interventions such as meditation, cognitive training, and auditory stimulation have been proposed. However, the comparative effectiveness of these interventions in improving sustained attention in Human-Computer Interaction (HCI) remains underexplored. This study investigates and constructs the efficacy of three widely used attention-enhancing techniques: binaural beats, cognitive training, and mindfulness meditation. Forty participants were assessed using continuous performance tests (CPTs) before and after undergoing one of the interventions. Our findings indicate that cognitive training had the most effect on improving attentional performance (mean difference = 0.06, $t = 3.16$, $p < 0.05$). These results highlight the effectiveness of interventions that actively engage working memory and cognitive control. We provide practical implications and design guidelines for HCI researchers and practitioners developing interactive systems aimed at supporting and improving sustained attention.

Keywords: sustained attention · EEG brainwave · continuous performance test · binaural beats · cognitive training · meditation

1 Introduction

Attention is a complex cognitive function that underlies everyday activities and supports related processes such as memory, learning, and executive control. Sustained attention refers to the ability to maintain focus over an extended period and is essential for tasks ranging from academic work to operating complex systems [1, 2]. However, attentional capacity typically declines over time, leading to performance degradation. Because of its practical importance, understanding how to measure and enhance sustained attention remains a key research objective.

Various experimental paradigms have been developed to assess attention, working memory, related cognitive processes, and information processing [1]. Performance on these tasks is typically evaluated through key metrics such as accuracy, reaction time, and error rates [3]. Widely used tasks include the Attentional Network Test (ANT), the Multiple Object Tracking task, and the Continuous Performance Task (CPT), each targeting different components of attention. In particular, the CPT is effective for detecting attentional lapses during prolonged and monotonous activities [4]. When combined with physiological measures such as electroencephalography, these paradigms enable a comprehensive assessment of attentional states.

Previous works have investigated a wide range of intervention strategies to support individuals experiencing difficulties with sustained attention, such as cognitive training, mindfulness meditation, and lifestyle-based approaches (e.g., physical activity or music) [5, 6]. Oberauer et al. showed that working memory based on cognitive training can yield improvements that sometimes transfer to academic skills, although these effects vary depending on factors such as training duration, baseline ability, and supervision [7]. By contrast, Martínez et al. found that mindfulness meditation produces more consistent outcomes, including reduced mind wandering, enhanced executive attention, and measurable neuroplastic changes in brain regions related to focus and self-regulation [8]. Lifestyle-based approaches, including physical activity and music, are accessible but generally produce modest effects [2, 9]. Despite these efforts, direct comparisons among different intervention strategies remain limited.

To address this gap, the present study evaluates three commonly used interventions, including cognitive training, meditation, and binaural beats, using a CPT paradigm. Participants performed a baseline assessment, followed by a single intervention session and a post-intervention test. The main aim is to compare the immediate effectiveness of these approaches in improving sustained attention and to provide evidence-based guidance for attention support strategies. The contributions of this work are:

- (1) A controlled, systematic comparison of three widely used intervention strategies for enhancing sustained attention
- (2) Behavioral evidence of differential effects on speed, accuracy, and error rates
- (3) Exploratory neural observations based on EEG band-power changes to inform future neural-adaptive and HCI applications.

2 Related Work

2.1 Measurement of Attention

Reliable assessment of attention is essential for detecting impairments and evaluating intervention outcomes. Among available paradigms, the Continuous Performance Task (CPT) is widely used to measure sustained attention and response inhibition in both clinical and experimental contexts [10]. During a CPT, participants respond to target stimuli while withholding responses to non-targets over an extended period, allowing multiple aspects of attentional performance to be evaluated. Key metrics, for instance, reaction time, omission errors, and commission errors, provide detailed indicators of attentional control [10, 11].

Previous studies have used CPT to monitor performance changes following cognitive training, mindfulness interventions, and other attention enhancement techniques. Cognitive training has been linked to reduced omission errors and improved accuracy, reflecting enhanced vigilance and control [12]. Mindfulness often produces modest changes in performance, including more consistent responses and reduced variability in reaction time, suggesting a more deliberate attentional strategy [13]. Findings on auditory interventions such as binaural beats are mixed, with some studies reporting improved performance and others finding no significant effects [14]. These inconsistencies highlight the need for controlled comparative studies.

Behavioral measures can be complemented by EEG signal, a non-invasive method for recording neural activity associated with attentional processes (Table 1) [15]. Changes in spectral power, such as increases in theta band or decreases in beta activity, have been linked to attentional lapses and mind wandering, while event-related potentials such as the P300 reflect allocation of attentional resources [16]. Combining behavioral tasks with physiological measures enables a more comprehensive assessment of attentional states.

Table 1. Brainwave frequencies and associated psychological states.

Type	Frequency (Hz)	Psychological State	Location
Delta	0–4	Deep rest	Frontal lobe
Theta	4–8	Deep relaxation	Thalamic region
Alpha	8–13	Day dreaming	Posterior regions
Beta	13–30	Alertness, anxiety, focus	Frontal and parietal lobes
Gamma	30–100	Sensory integration	Somatosensory cortex

2.2 Enhancing Attention Interventions

Previous research has explored several approaches to enhancing attention, including cognitive training, meditation, and auditory stimulation such as binaural beats [17–19]. These methods differ in mechanisms, but all aim to improve attentional control.

Cognitive training, particularly working memory training, has demonstrated potential benefits. Meta-analytic evidence suggests improvements in attentional performance, although the extent to which these gains transfer beyond trained tasks remains debated [20]. Adaptive tasks such as the Dual N Back paradigm have been shown to improve performance on related cognitive tasks, indicating enhanced attentional capacity [18]. Our study aims to contribute to this debate by providing a direct comparison of cognitive training against other interventions.

Meditation has also been associated with improvements in attention through changes in neural oscillatory activity. De Vuyst et al. [21] recorded EEG during focused attention meditation and reported that alpha theta cross-frequency dynamics were associated with greater attentional engagement. Travis and Shear proposed a model distinguishing focused attention, open monitoring, and self-transcending practices, each characterized

by distinct neural signatures [22]. Tang et al. demonstrated that mindfulness training improves executive attention and induces neuroplastic changes in brain regions related to self-regulation and focus [23]. Additional studies indicate that meditation can reduce mind wandering and enhance present moment awareness, although sustained practice is often required for measurable benefits [17].

Binaural beats have been proposed as a non-invasive method for modulating brain activity. Some studies report improvements in vigilance and alertness, whereas others find minimal or no effects on attention tasks [24]. These inconsistent findings underscore the need for direct comparisons across intervention types.

By evaluating cognitive training, meditation, and binaural beats within a unified experimental framework, the present study aims to clarify their relative effectiveness in enhancing sustained attention and to address gaps in the existing literature.

3 Methodology

A controlled laboratory experiment was conducted to compare the effects of cognitive training, meditation, and binaural beats on sustained attention, with a passive control group for baseline comparison. The study followed a pre-test, intervention, post-test design. Participants were randomly assigned to one of four conditions: cognitive training, meditation, binaural beats, or control. At baseline and post-intervention, all participants completed a Continuous Performance Task (CPT) to assess sustained attention using reaction time, omission errors, and commission errors.

3.1 Procedure

Each experimental session lasted approximately 90 min and was conducted in a controlled laboratory environment. The overall experimental setup, including the EEG acquisition system and participant interaction with the computer-based task, is illustrated in Fig. 1. The protocol consists of three phases: baseline assessment, intervention, and post-intervention assessment. Participants provided informed consent before the experiment and received compensation for their participation.

Pre-intervention Phase. Participants completed a brief questionnaire on alertness, caffeine intake, and sleep quality, followed by a short practice trial of the CPT to ensure understanding. They then performed CPT1 (baseline) for 10 min continuously while EEG and behavioral metrics were recorded.

Intervention Phase. Participants immediately completed a 15-min session corresponding to their assigned condition. The cognitive training group performed a Dual N-Back task, the meditation group engaged in guided breathing meditation, the binaural beats group listened to an auditory track through headphones, and the control group performed a neutral activity such as reading. EEG was recorded continuously.

Post-Intervention Phase. Participants then completed a second CPT (CPT2) for 10 min. CPT2 used a different response rule to reduce practice effects. Afterward, a short questionnaire assessed participants' subjective perceptions of intervention effectiveness, followed by debriefing.



Fig. 1. Experimental protocol setup. Left: the Emotiv EPOC X headset used for EEG signal acquisition. Right: experimental setup where a participant wears the headset while performing a computer-based attention task.

3.2 Intervention for Attentional Enhancement

Participants experienced one of three attentional interventions or a neutral control activity, each designed to influence focus through different mechanisms.

The cognitive training group performed the Dual N-Back task, a demanding working memory paradigm known to engage attentional control and executive processes [16]. The task was presented on a desktop computer and began with a brief practice round of approximately 60 s to ensure understanding. After practice, participants completed successive task blocks until a total of 15 min was reached. Each block lasted about two minutes, providing short pauses that helped reduce fatigue and maintain engagement during electroencephalography recording.

The meditation group completed a guided focused breathing session using a standardized recording from the Headspace application to ensure consistency across participants [15]. Participants sat comfortably with eyes closed and followed instructions directing attention to the breath and gently returning focus when distracted. The goal was to induce a calm and centered attentional state. Electroencephalography was recorded continuously without providing feedback.

The binaural beats group listened to an auditory track designed to promote focused attention through frequency-specific stimulation. Binaural beats are created by presenting slightly different tones to each ear, producing a perceived rhythmic beat corresponding to the frequency difference. This stimulation is proposed to entrain neural oscillations associated with alertness and concentration, particularly in beta and gamma ranges, although empirical findings remain mixed [25]. While findings are promising, results remain mixed, and further controlled studies are needed to confirm their consistency and long-term effectiveness.

The control group engaged in a neutral activity for 15 min (e.g., reading, writing, or drawing). These activities were low in cognitive demand and unrelated to attention training. This condition controlled for practice effects and general factors such as fatigue or boredom, allowing any performance improvements in the intervention groups to be interpreted relative to baseline learning effects.

All interventions were conducted in the same laboratory environment with participants seated and wearing the electroencephalography headset. An experimenter monitored compliance with the protocol throughout the session.

3.3 Cognitive Measurement Task

The Continuous Performance Task (CPT) is a standard measure of sustained attention based on a “go/no-go” paradigm, wherein participants respond to frequent target stimuli while withholding responses to non-targets [10]. Its repetitive structure is designed to challenge the ability to maintain consistent attention over time. In this study, the CPT was administered in two phases, including CPT1 and CPT2, to capture attentional performance before and after the intervention.

In CPT1 (pre-intervention), participants were instructed to press the ‘X’ key whenever the target letter ‘X’ appeared and the SPACE bar for all other letters. CPT2 (post-intervention) introduced a more complex rule to reduce procedural learning effects. Participants pressed the ‘C’ key only when the letter ‘C’ immediately followed the letter ‘V’ (the ‘V-C’ sequence) and pressed SPACE for all other stimuli. This rule required continuous monitoring of stimulus history, increasing demands on working memory and sustained attention.

Performance in both CPT phases was evaluated using four key behavioral metrics [11]: accuracy, reaction time, omission errors (missed targets), and commission errors (responses to non-targets). Omission errors reflect lapses in attention, whereas commission errors indicate impulsive responding.

3.4 Data Acquisition and Analysis

Participants

Forty healthy adults aged 18 to 30 years (mean age 22.5 ± 3.1 years) participated. Participants were randomly assigned to one of four conditions: cognitive training, meditation, binaural beats, or control. Individuals with neurological disorders, psychoactive medication use, or extensive prior experience in medication or structured cognitive training were excluded. Extensive experience was defined as regular meditation practice at least three times per week for six months or prior structured brain training use within the past year, based on self-report. Two subjects were excluded due to technical issues, resulting in final group sizes of $n = 9$ (binaural), 10 (cognitive), 10 (meditation), and 11 (control). Participants had normal or corrected vision and were instructed to obtain adequate sleep and avoid caffeine before testing.

All procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki. The study involved only non-invasive behavioral interventions with

healthy adult volunteers, and written informed consent was obtained from all participants before performing tasks. It was deemed exempt from formal local ethics committee approval (in line with institutional guidelines for minimal-risk studies).

Data Acquisition

Brain activity was recorded using the Emotiv EPOC X headset (Emotiv Inc.), a 14-channel wireless EEG device with a sampling rate of 128 Hz [26]. The Emotiv system has been used in prior EEG studies, where it demonstrated adequate signal quality for monitoring cognitive activity, supporting its use in the present experiment [27, 28]. Additionally, Emotiv headsets have also been employed to assess mental states such as engagement and cognitive effort during interactive tasks, indicating their suitability for HCI applications [29]. Participants were fitted with the device in a quiet laboratory environment, and electrodes were positioned according to the international 10–20 system (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4), with reference sensors at P3 and P4 [30]. And signal quality was checked before starting the tasks. This configuration provides coverage of frontal and parietal regions implicated in attentional control. Signals were acquired within a 0.2–45 Hz bandwidth [30].

EEG data were band-pass filtered (0.5–40 Hz) before analysis. Recordings were visually inspected, and segments with excessive movement or unstable electrode contact were excluded. Ocular and muscle artifacts were mitigated using automated threshold-based rejection and channel-quality metrics provided by the Emotiv system. Advanced artifact correction methods (e.g., ICA) were not applied; therefore, EEG findings are interpreted as exploratory at the spectral level.

Sustained attention was measured using Continuous Performance Tests (CPTs). Participants completed a baseline CPT (CPT1), followed by the assigned intervention, and then a post-intervention CPT (CPT2) with modified stimulus rules. Behavioral outcomes included accuracy, reaction time, omission errors, and commission errors.

Data Analysis

Statistical analyses were conducted to evaluate changes in behavioral performance across conditions. Descriptive statistics (mean $\pm$ SD) were computed for reaction time, accuracy, omission errors, and commission errors for both CPT1 and CPT2.

A mixed design analysis examined the effects of condition (pre versus post) and intervention type. Significant results were followed by paired t-tests comparisons within groups and one-way ANOVA analyses of gain scores between groups. We applied the Bonferroni correction to post hoc comparisons to control Type I error within each family of tests associated with a given behavioral metric, rather than across all possible comparisons simultaneously. Additionally, we computed effect sizes (Cohen's d for within-group changes and partial η^2 for ANOVA effects) to gauge the practical significance of any findings. All statistical analyses were executed in R (version 4.4.1), and a significance level of $\alpha = 0.05$ was applied to all tests.

For EEG data, spectral analysis was conducted to estimate power in canonical frequency bands (delta through gamma) during CPT1 and CPT2 to examine neural activity associated with attentional performance. No event-related potential analyses were performed. In this paper, we primarily report behavioral outcomes and include electroencephalography findings only where they inform interpretation. The wealth of EEG data

(14 channels $\times$ 2 sessions $\times$ multiple metrics) is beyond the scope here, but spectral measures can indicate patterns such as increased frontal midline theta associated with sustained attention or reductions in alpha activity linked to mind wandering [31].

4 Results

The interventions produced distinct effects on sustained attention performance. Table 2 summarizes CPT results before and after the intervention, and Fig. 2 illustrates changes in key metrics, where higher accuracy and lower error rates indicate better performance. Cognitive training showed the most consistent improvements, including increased accuracy, faster responses, and reductions in omission and commission errors. Binaural beats primarily reduced omission errors and produced modest accuracy gains, with little effect on reaction time or commission errors. Meditation did not significantly improve accuracy or error rates and was associated with slower reaction times, suggesting a more deliberate response style. The control group also demonstrated performance improvements, particularly faster reaction times, indicating practice effects from repeated task exposure.

4.1 Behavioral Outcomes

Table 2 summarizes CPT performance before and after the intervention for all groups. Cognitive training produced the most consistent improvements across all metrics, whereas binaural beats primarily improved accuracy and reduced omission errors. Meditation mainly increased reaction time, and improvements in the control group likely reflect practice effects from repeated task exposure.

To investigate intervention effects, a one-way repeated measures ANOVA was conducted with condition (CPT1 vs. CPT2) and intervention group (binaural beats, cognitive training, meditation, and control). A significant main effect of condition indicated overall performance improvement from CPT1 to CPT2. In Fig. 2, a post-hoc test indicated that participants in the cognitive training group showed a significantly greater increase in accuracy ($MD = 0.06$, $t = 3.16$, $p = 0.01$) compared to the other groups, with a moderate effect size ($d = 0.66$).

Omission error decreased significantly in both the binaural beats group ($MD = -0.03$, $t = 5.99$, $p < 0.001$) and the cognitive training group ($MD = -0.04$, $t = 2.57$, $p < 0.05$). For commission errors, only the cognitive training group showed a significant reduction ($MD = -0.02$, $t = 4.15$, $p < 0.01$). Reaction time also changed significantly in all groups except the binaural beats. Both cognitive training ($MD = -0.11$, $t = 11.54$, $p < 0.001$) and the control group ($MD = -0.11$, $t = 12.41$, $p < 0.001$) showed comparable reductions, whereas the meditation group exhibited the largest increase in reaction time ($MD = 0.15$, $t = 3.67$, $p < 0.01$). No significant change in reaction time was observed for binaural beats ($MD = 0.06$, $t = 1.74$, $p = 0.13$).

Table 2. Summary of Independent t-test results for CPT performance

Metrics	Groups	CPT1	CPT2
Accuracy	Binaural beats *	0.90 ± 0.04	0.93 ± 0.04
	Cognitive training *	0.90 ± 0.06	0.95 ± 0.04
	Meditation	0.88 ± 0.05	0.91 ± 0.09
	Control *	0.89 ± 0.05	0.94 ± 0.05
Reaction time	Binaural beats	0.49 ± 0.06	0.42 ± 0.05
	Cognitive training ***	0.50 ± 0.03	0.39 ± 0.04
	Meditation **	0.57 ± 0.11	0.42 ± 0.12
	Control ***	0.50 ± 0.05	0.39 ± 0.07
Omission error	Binaural beats ***	0.08 ± 0.03	0.04 ± 0.02
	Cognitive training *	0.08 ± 0.05	0.04 ± 0.03
	Meditation	0.09 ± 0.04	0.09 ± 0.05
	Control	0.08 (0.05)	0.08 (0.03)
Commission error	Binaural beats	0.02 (0.01)	0.02 (0.03)
	Cognitive training **	0.03 (0.02)	0.01 (0.01)
	Meditation	0.04 (0.03)	0.04 (0.04)
	Control	0.02 (0.01)	0.03 (0.03)

Note: Mean (Standard Deviation); * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

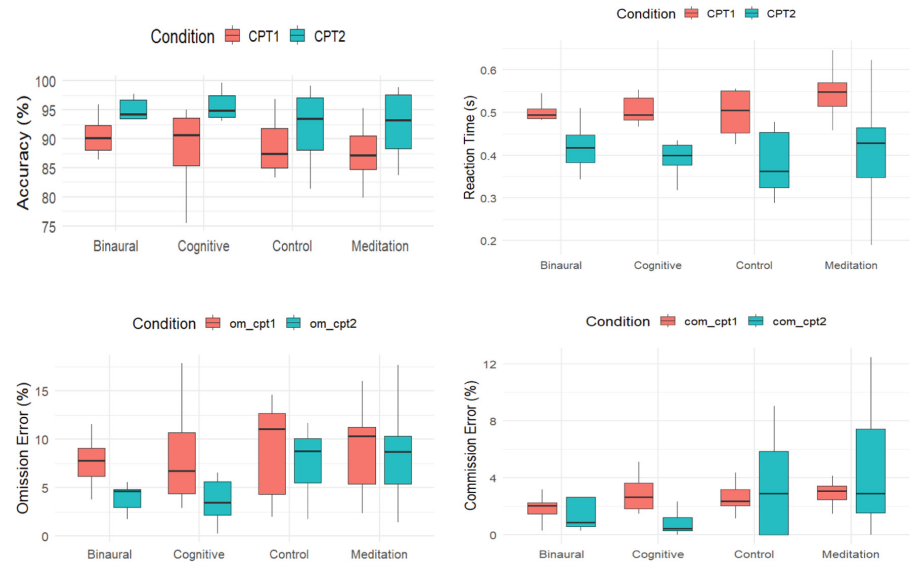


Fig. 2. Pre-post CPT performance across interventions (accuracy, reaction time, omissions, and commissions errors)

4.2 EEG Analysis

Pre–post changes in EEG band power between CPT1 and CPT2 were examined across four groups (binaural beats, cognitive training, meditation, control) in six regions of interest (AF3/AF4, F3/F4, O1/O2). The spatial distribution of band-power changes across groups and sessions is visualized in Fig. 3.

The binaural beats group demonstrated widespread increases dominated by theta activity, particularly at posterior sites (O1/O2), with additional increases at right frontal locations. Changes in alpha were modest, whereas beta and gamma activity showed minimal variation. The cognitive training group exhibited prominent increases in frontal theta (AF3/AF4, F3/F4), accompanied by moderate alpha enhancement, with limited changes in higher frequency bands. The meditation group showed the largest and most widespread increases across frequency bands, with pronounced theta and alpha elevations at both frontal and posterior regions. In contrast, the control group displayed smaller and less consistent changes, including modest theta increases and reduced frontal gamma activity from CPT1 to CPT2.

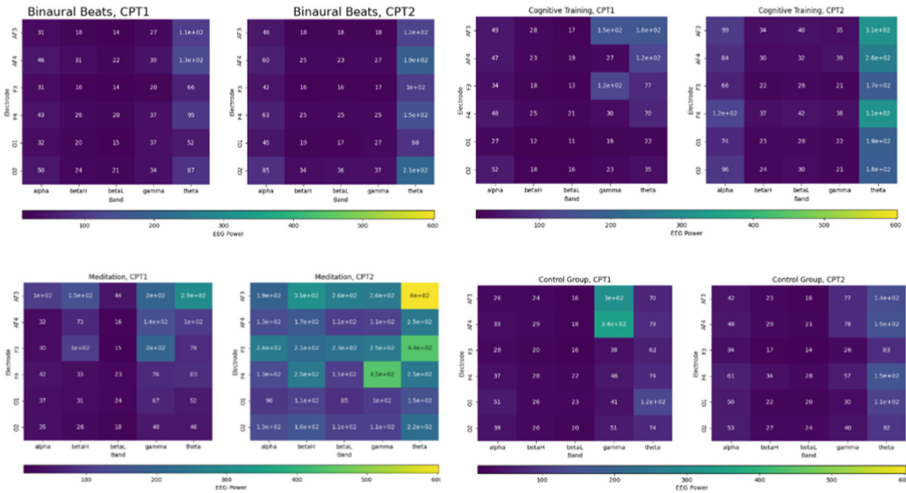


Fig. 3. EEG band-power heatmaps for the four groups across CPT sessions. Each pair of panels shows CPT1 (pre-intervention) on the left and CPT2 (post-intervention) on the right.

5 Discussion

Our findings indicate that short-term attentional interventions differ substantially in their immediate effectiveness. Cognitive training produced the most consistent improvements across multiple behavioral metrics, including accuracy, reaction time, and error reduction. In contrast, binaural beats primarily enhanced vigilance, as reflected by fewer omission errors, while meditation induced slower responses without clear accuracy gains. These results highlight that different interventions may modulate distinct components of attention rather than producing uniform benefits.

5.1 Efficacy and Mechanisms of Each Intervention

The cognitive training produced robust improvements across performance measures, indicating that even brief intensive cognitive exercise can temporarily enhance attentional control. The demanding nature of the task likely increased engagement and arousal, facilitating transfer to the subsequent CPT. Practicing updating and inhibitory processes may have improved target detection and discrimination, consistent with prior findings on short-term benefits of working memory training [30]. The moderate effect size observed for accuracy ($d = 0.66$) suggests a practically meaningful improvement. Although the durability and generalizability of these gains remain uncertain, our design minimized direct practice effects by altering CPT rules, supporting the interpretation of genuine skill transfer within a similar task context. Importantly, while the control group showed comparable improvements in reaction time, it did not exhibit gains in accuracy or error rates, indicating that cognitive training uniquely enhanced the quality of attentional performance rather than merely speeding responses [32].

Binaural beats selectively reduced omission errors, suggesting improved vigilance during monotonous task performance. This pattern is consistent with studies reporting that beta-frequency stimulation may help maintain alertness without substantially improving response speed or inhibitory control [25, 33]. Thus, binaural stimulation may reduce attentional lapses rather than broadly enhancing cognitive performance.

Meditation produced a different profile, characterized by slower responses without significant improvements in accuracy or errors. This effect may reflect a shift toward a calmer, less reactive cognitive state rather than impaired attention. Short-term mindfulness practice has been associated with increased deliberation and reduced impulsivity, which may lead to slower but potentially more controlled responding [34]. However, the absence of accuracy gains suggests that a single brief session may be insufficient to produce measurable behavioral improvements.

A critical finding of our study was the significant improvement observed in the control group, most notably a reduction in reaction time ($MD = 0.11$, $t = 12.41$, $p < 0.001$) comparable to that of the cognitive training group. This strongly suggests that reaction-time improvements primarily reflect practice-related motor familiarity and procedural learning rather than intervention-specific speed enhancement. Repeated exposure to the CPT likely reduced task novelty and improved stimulus–response mapping efficiency across sessions. This finding provides a clear demonstration of practice effects, a well-documented phenomenon in repeated-measures cognitive tasks such as the CPT [35]. Crucially, however, only the cognitive training group demonstrated significant improvements in accuracy and reductions in omission and commission errors. This distinction indicates that while task repetition alone was sufficient to enhance response speed, cognitive training uniquely strengthened attentional control and improved the quality of performance.

5.2 Differential Neural Signatures of Attentional Interventions

Pre–post spectral changes were dominated by theta-band modulation across conditions, with more modest effects in alpha. Cognitive training produced focal increases in frontal theta power, a neural signature associated with working memory and top-down

attentional control [20, 30]. This pattern supports the behavioral findings and suggests engagement of executive control mechanisms.

Unlike cognitive training, meditation elicited the largest and most widespread increases in slow-frequency activity, particularly theta and alpha, across frontal and occipital regions. Such patterns are consistent with prior reports linking mindfulness practice to relaxed yet stable attentional states [21, 22]. However, these neural changes were not accompanied by behavioral improvements; participants showed no gains in accuracy or errors and responded more slowly after the intervention. Rather than reflecting impaired attention, this slowing may indicate a shift toward a more deliberate, non-reactive cognitive style. Short-term mindfulness has been associated with reduced impulsivity and calmer responding, supported by evidence of increased prefrontal activation and reduced sympathetic arousal [34]. Thus, meditation may enhance attentional stability in ways not captured by speed-based CPT metrics, highlighting a dissociation between neural state changes and task performance.

Relative to CPT1, CPT2 under binaural beats showed a theta-dominant increase that was largest posteriorly (notably O2) with a smaller rise at right frontal sites (AF4/F4); alpha changes were modest, and beta/gamma were largely unchanged. This topography is consistent with sensory entrainment that strengthens rhythmic activity in posterior networks while only weakly engaging frontal control circuits. In contrast, the control group showed minimal, non-coherent changes (including reduced frontal gamma), supporting the interpretation that the strong patterns above are intervention-specific rather than mere repetition effects.

5.3 Limitations and Future Directions

This study produced clear findings, but several limitations constrain interpretation and highlight directions for future work. The relatively small sample size ($N = 40$, with 9 to 11 participants per group after exclusions) limited statistical power, particularly for outcomes with smaller effects such as commission errors. Although the study was adequately powered to detect medium-to-large effects, it was likely underpowered for small effects, which may explain the absence of significant findings in certain measures (e.g., commission errors in control groups or meditation-related accuracy gains). Therefore, non-significant results should not be interpreted as definitive evidence of no effect. A larger sample would allow more precise effect-size estimation and more reliable detection of subtle intervention differences.

Each intervention was administered only once for 15 min, which restricts conclusions about durability; repeated or longer sessions of daily cognitive training or meditation might yield different trajectories of behavioral and neural change. Importantly, because each intervention was delivered only once and evaluated immediately afterward, the present findings reflect short-term, state-level modulation of attention rather than sustained or long-term improvements. It remains unclear whether repeated exposure to these interventions would lead to cumulative benefits, stable trait-level changes, or transfer to real-world attentional demands. Therefore, the current results should be interpreted as evidence of immediate post-intervention effects, and future longitudinal studies with multi-session protocols are required to assess the sustainability and durability of these attention-enhancement strategies.

In addition, our sample lacked demographic diversity, which constrains the generalizability of the results beyond a narrow age and educational range. The short-term, lab-based context further limits ecological validity, as the immediate improvements observed here may not extend to everyday settings; longitudinal and in-the-wild studies are needed to assess persistence and real-world transfer. Although EEG was incorporated, our analysis focused primarily on band power in predefined regions of interest. More fine-grained neural markers, such as P300 or ML-based classification approaches, were beyond the scope of the present study. Future work should expand toward connectivity analyses, cross-frequency coupling, ERP components, and predictive modeling to more comprehensively characterize intervention-specific neural signatures.

6 Conclusion

In this study, we evaluated the effectiveness of cognitive training, binaural beats, and meditation as interventions for enhancing sustained attention. The results indicate that these approaches influence attention differently, underscoring the complexity of attentional processes and the need for tailored strategies. Cognitive training emerged as the most effective intervention, producing consistent improvements in accuracy and error-related measures, suggesting strengthened attentional control mechanisms. From an HCI perspective, these findings support the design of interactive systems that incorporate cognitively engaging activities to sustain user focus. Future work should investigate long-term effects and underlying neural mechanisms to guide applications in clinical and educational settings.

7 Disclosure of Interests.

The authors have no competing interests to declare that are relevant to the content of this article.

Acknowledgments. We would like to express our gratitude to all participants in this study.

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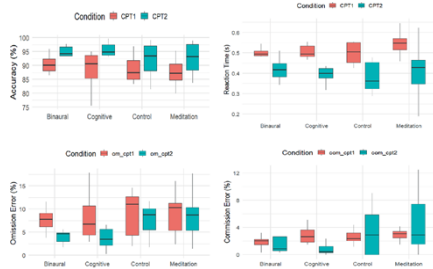
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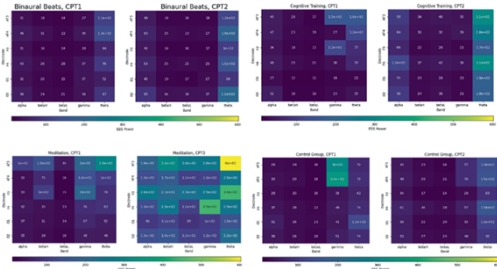
Author Queries

Chapter 26

Query Refs.	Details Required	Author's response
AQ1	Please confirm if the inserted city name is correct. Amend if necessary.	

Alternative Texts for Your Images, Please Check and Correct them if Required

Page no	Fig/Photo	Thumbnail	Alt-text Description
5	Fig1		The image is divided into two parts. On the left, there is a close-up view of a black wearable device designed to be worn on the head, featuring multiple sensors or electrodes attached to flexible arms extending from a central band. On the right, a person is seated at a desk working on a laptop, wearing the same type of head device. The laptop screen is mostly blank, while a larger monitor behind the laptop displays a graph with multiple lines and a colorful background. The setting appears to be an indoor workspace with wooden furniture.
9	Fig2		The image contains four box plots comparing two conditions across four categories: Binaural, Cognitive, Control, and Meditation. Top left plot shows Accuracy (%) with two conditions labeled CPT1 (red) and CPT2 (blue). Accuracy ranges roughly from 75% to 100%, with CPT2 generally showing higher median accuracy than CPT1 across all categories. Top right plot shows Reaction Time (seconds) for the same conditions and categories. Reaction times range from about 0.2 to 0.6 seconds, with CPT2 generally showing faster (lower) reaction times than CPT1. Bottom left plot shows Omission Error (%) with conditions labeled om_cpt1 (red) and om_cpt2 (blue). Omission errors range from 0 to about 18%, with om_cpt2 generally showing lower median omission errors than om_cpt1, especially in the

Page no	Fig/Photo	Thumbnail	Alt-text Description
			Cognitive category. Bottom right plot shows Commission Error (%) with conditions com_cpt1 (red) and com_cpt2 (blue). Commission errors range from 0 to about 12%, with mixed results between conditions across categories, but generally com_cpt2 shows higher variability. Overall, the figure compares performance metrics under two conditions across four task types, highlighting differences in accuracy, reaction time, and error rates.
10	Fig3		Eight heatmaps arranged in two rows and four columns, each representing EEG power across different frequency bands (alpha, beta1, beta2, gamma, theta) and brain regions (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4). The top row shows data for Binaural Beats (CPT1 and CPT2) and Cognitive Training (CPT1 and CPT2), with predominantly low EEG power values indicated by dark purple shades and some higher values in the theta band. The bottom row shows data for Meditation (CPT1 and CPT2) and Control Group (CPT1 and CPT2), with Meditation CPT2 displaying the highest EEG power values, especially in the theta band, indicated by yellow and green colors. Each heatmap includes a color scale bar ranging from 0 to 600 EEG power units, with colors transitioning from dark purple (low) to yellow (high). Numerical values are overlaid on each cell, showing specific EEG power measurements. The figure compares EEG power distributions across different conditions and sessions.

