NeuroRegulation

The Official Journal of ISNR

INTERNATIONAL SOCIETY FOR NEUROREGULATION & RESEARCH

Volume 12, Number 1, 2025

NeuroRegulation

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NeuroRegulation

ISNR
INTERNATIONAL SOCIETY FOR NEUROREGULATION & RESEARCH

Volume 12, Number 1

2025

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NeuroRegulation

Nonmusicians Experience Early Aging on Working Memory Tasks Compared to Musicians

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Abstract

Background. Previous studies on musicians have revealed better working memory (WM) abilities in musicians than in nonmusicians. This study investigates whether the deterioration of WM with aging is slowed in musicians relative to nonmusicians by assessing their performances across an age continuum. **Methods.** A cross-sectional descriptive mixed design was used. The study involved 150 participants, 75 musicians, and 75 nonmusicians, with 15 musicians and 15 nonmusicians in each age group (10–19.11, 20–29.11, 30–39.11, 40–49.11, and 50–59.11). Simple and complex spans were measured to assess the participant's WM capacity. Backward Digit Span (BDS) maximum and Reading Span Percent Correct Score Weighted (RS PCSW) scores were calculated. **Results.** Two-way ANOVA revealed significant main effects of musicianship ($p < .001$) and age ($p < .05$) on BDS maximum and RS PCSW scores. A "moderate to large" effect size was noted ($\eta p2 = 0.062$ to 0.455). Interaction effects were observed for BDS maximum ($p = .022$) and approached significance for RS PCSW ($p = .06$). Post-hoc analysis revealed that age effects were exclusively present in nonmusicians. **Conclusion.** Musical training can significantly reduce the cognitive decline associated with aging. It improves WM abilities, thereby minimizing the deleterious effects of aging.

Keywords: music training; age effect; cognition; working memory; backward digit span; reading span

Citation: Shankar, K., & Uppunda, A. K. (2025). Nonmusicians experience early aging on working memory tasks compared to musicians. *NeuroRegulation, 12*(1), 2–11. https://doi.org/10.15540/nr.12.1.2

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Introduction

The auditory system alters as we age, both physiologically and physically. These alterations may impact different parts of the auditory system, ranging from the external auditory canal to the auditory cortex of the brain, resulting in age-related hearing impairments such as presbycusis (Howarth & Shone, 2006). Even when hearing sensitivity is adequately preserved at conventional audiometric frequencies, aging may cause a loss in perceptual and cognitive ability (Houtgast & Festen, 2008). Thus, aging is connected with a decline in cognitive skills, with working memory (WM) impairment being a significant contributing component. WM refers to the ability to maintain and process information simultaneously while performing complex tasks. Attempts to prevent WM deterioration may assist older people in improving their quality of life (Matysiak et al., 2019). Finding ways to lessen age-related perceptual, cognitive, and neurological decline is crucial in a community that is aging. One such skill is learning music.

Research in the last decade has highlighted professional musicians' superiority in sensory, motor, and cognitive abilities compared to nonmusicians (Barrett et al., 2013; Kraus & Chandrasekaran, 2010). Music training is known to induce functional and structural brain plasticity (George & Coch, 2011; Talamini et al., 2016). Professional musicians are proven to have higher "active auditory association areas" than nonmusicians (Gaab & Schlaug, 2003). Therefore, musicians are commonly viewed as models for researching plasticity over their lifetime (Barrett et al., 2013; Kraus & Chandrasekaran, 2010). Musicians are said to outperform nonmusicians on memory tasks (Bregman, 1990). WM is reported to be strengthened in musicians (Bregman, 1990; Martin, 2009). Nonetheless, some research indicates that musicians and nonmusicians function similarly in terms of short-term memory, WM, reasoning, or executive skills (Boebinger et al., 2015; Helmbold et al., 2005). Thus, the WM performance is somewhat better for musicians than for nonmusicians. Still, the literature is unclear regarding the former's potentially superior cognitive performances compared to the latter.

Musicians are deemed to possess greater auditory WM (Chan et al., 1998; Talamini et al., 2016) and verbal and nonverbal IQ (Schellenberg, 2006). In a previous meta-analytic study, it was noted that when the participants chosen were younger, and the stimuli were verbal or tonal, musicians outperformed nonmusicians on memory tests; however, the outcomes were different when the participants selected were adults, and the stimuli were visual and spatial (Talamini et al., 2017). In another meta-analysis, 13 studies were considered. Studies on aging musicians above 59 years of age assessed their cognitive abilities. The results indicated a clear advantage of music training in improving cognitive abilities in older adults (Román-Caballero et al., 2018).

Therefore, on cognitive tasks, age and music training have opposite impacts. According to a recent systematic review, the median age-related cognitive impairment prevalence was 19%, with a range of 5.1 to 41% in adults older than 50 years of age (Pais et al., 2020). The incidence was between 22 and 76.8%, with a median of 53.97 per 1,000 people. Because age-related processing deficits are highly prevalent and have detrimental effects on the older population, it is crucial to prevent, mitigate, or postpone them. Thus, older individuals may benefit from any effort to halt WM deterioration. Nonetheless, the literature has disagreement over the effectiveness of techniques like WM training methods (Matysiak et al., 2019).

Music is a known facilitator that causes improvements in WM abilities. Several microtonal changes are found in Carnatic music, which are absent in Western classical music (Krishnaswamy, 2004). This intrinsic microtonal emphasis in Indian music can be used to process temporal, pitch, and intensity changes in sound over different frequency channels, resulting in improved binaural and temporal resolution (Mishra et al., 2014). Until now, no study has looked at a range of ages to thoroughly examine how aging affects cognitive skills in musicians and nonmusicians. This research will provide insight into when aging begins and when its degenerative effects manifest in musically trained and untrained groups. The results on musicianship advantage are also not definitive because a few studies have demonstrated that groups of musicians and nonmusicians perform similarly on such tasks. Thus, we investigated the WM capacities of vocalists of different ages and compared the results to cohorts of nonmusicians of similar ages.

Therefore, the current study aimed to examine the auditory cognitive capacities of musicians and nonmusicians throughout a range of ages. The goal was to investigate how age affected WM tasks in musicians and nonmusicians. Tests such as the Backward Digit Span (BDS) and reading span (RS) were administered to determine WM skills. Participants in a continuum of age ranges were assessed in the musician and nonmusician groups.

Methods

A cross-sectional descriptive study with a mixed design was carried out. Using convenient sampling, the individuals were chosen. Before the study began, all participants were informed of its purpose and objective. The participants were asked to sign an informed consent form if they were willing to participate, and signed consent was obtained before commencing data collection. The investigation complied with "All India Institute of Speech and Hearing's ethical guidelines for bio-behavioral research involving human subjects" (Venkatesan & Basavaraj, 2009).

Participants

The study evaluated 150 participants (*N* = 150), 75 musicians and 75 nonmusicians, in five age groups: 10–19.11 years, 20–29.11 years, 30–39.11 years, 40–49.11 years, and 50–59.11 years. In each age group, there were 15 musicians and 15 nonmusicians. According to Muñoz-Pradas et al. (2021) and Sluzenski et al. (2006), WM—which consists of components like the phonological loop, visuospatial sketch pad, central executive, and episodic buffer—is known to develop adult-like capacities from ages 8 to 9, 11 years, 14 to 15 years, and by six years, respectively. The BDS task, which measures WM ability, reaches adult-like maturation by 11 to 11.5 years of age (Reynolds et al., 2022), with an average BDS score of 4.2, which is comparable to that reported for adults (Gignac, 2015; Gignac & Weiss, 2015). Another study indicated that auditory processing skills matured only after age 11 (Yathiraj & Vanaja, 2015). Based on the information from the above studies, the specified age ranges were chosen for the study.

The Mini-Mental State Examination (MMSE; Folstein et al., 1975) was used to test older individuals (aged 50 to 59.11 years) for cognitive capacities before they took part in the study. Individuals with scores higher than 24 were included in the research study. Elderly individuals who scored above 50% on the Screening Checklist for Auditory Processing in Adults (SCAP-A) were excluded from the study (Vaidyanath & Yathiraj, 2014). For the younger age group, the participants had received vocal training in Carnatic classical music for a minimum of 5 years in the youngest age group, while for the other age groups the training received was at least 10 years. The study did not include the instrumentalists.

Test Environment

All audiological evaluations took place in a calm setting with sufficient ventilation and light. To ensure that the tested sounds could be clearly heard and fairly evaluated, a "silent setting" with low background noise levels was used.

Instrumentation, Materials, and Software

Using MATLAB (version R 2014a) loaded on an HP laptop and the maximum likelihood procedure (MLP; Grassi & Soranzo, 2009), the absolute threshold test was conducted to evaluate hearing thresholds. A calibrated immittance equipment (Path Medical Sentiero) was used to conduct tympanometry and acoustic reflex tests. Transient-evoked otoacoustic emissions (TEOAEs) were recorded using the Maico Ero Scan screening otoacoustic emission (OAE) instrument. Using an HP laptop and Smriti-Shravan (Kumar & Sandeep, 2013), an institutional software with an audio-cognitive training module, the auditory cognitive WM tests were conducted. Threshold estimations and cognitive testing were performed using Sennheiser HD-569 high-fidelity headphones (Denmark, Germany). The stimulus was delivered through headphones at 70 dBSPL calibrated using SLM (Larsen and Davis Sound Advisor Model-831c-Type 1 SLM with AEC201 ear simulator with a frequency range up to 16 kHz) with the laptop volume set to deliver 70 dBSPL.

Procedure

The test was performed in two phases. In the initial phase, a brief case history was obtained. Subsequently, the MMSE and SCAP-A tests were conducted (limited to older adults aged 50–59.11 years). Basic audiological tests were also performed, including OAE, immittance, and pure tone audiometry. The second phase involved administering cognitive tests.

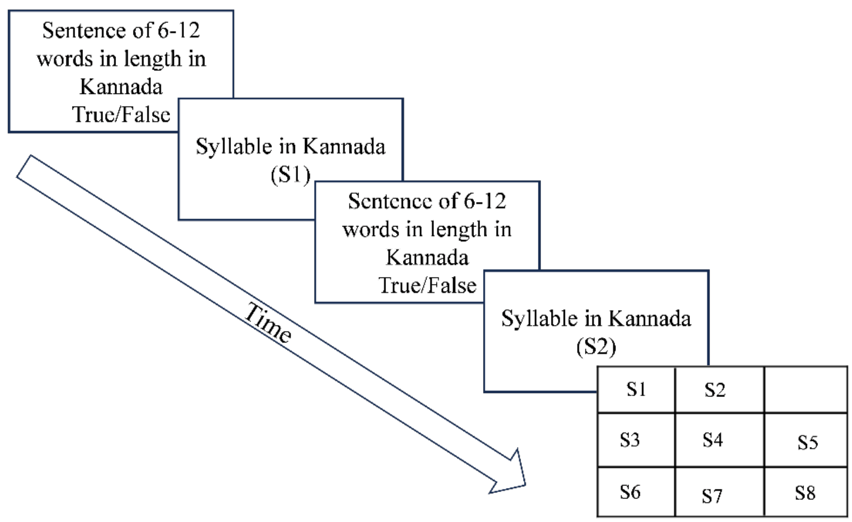
The absolute threshold test was used for threshold estimation using the MLP approach. Pure tones with 10 ms cosine-squared envelopes and frequencies ranging from 250 Hz to 8 kHz were presented binaurally. The psychometric function that gives the maximum likelihood of getting the response is displayed as the next stimulus in MLP to maximize the potential of reaching the threshold with fewer trials. Binaurally delivered thirty stimuli were used to test thresholds. The yes–no method was employed, in which individuals reported hearing the sound or not. Thus, MLP was used to determine each participant's pure tone thresholds for both ears. The threshold was the mean between the level not heard and the level last heard by the participant. The thresholds were compared to the absolute threshold values of MLP obtained on 30 individuals. They were not a part of the study participant sample. They were selected through the convenience sampling method. Their hearing thresholds were within 15 dBHL at all audiometric frequencies, and their MLP thresholds were taken as a reference for comparison and threshold determination. Tympanometry was assessed using a 226 Hz probe tone frequency at 85 dBSPL and increasing pressure from −400 to +200 daPa at a rate of 200 daPa/s. Reflex testing was done at 500 and 1000 Hz.

Auditory Cognitive Tests. Cognitive capacities, notably WM, deteriorate with aging (Matysiak et al., 2019). Many cognitive tasks, such as understanding different languages, logical thinking, and solving problems, depend on WM (Vuontela et al., 2003). The BDS and RS tests from Smriti Shravan software were used in assessing musicians' and nonmusicians' auditory WM abilities as they are the most valid measures of WM capacities in humans (Conway et al., 2005).

Backward Digit Span Test. Eight digitally recorded Kannada numbers (between 1 to 8, except 2) with a sampling frequency of 44.1 kHz were presented binaurally at an intensity of 70 dBSPL. The interstimulus interval was 1 s. Participants were instructed to enter them in reverse order according to how they heard the numbers. A practice trial was conducted. The test began with two digits. Following each correct response, the subsequent series of numerals included one additional digit. Each incorrect response resulted in the deduction of one of the digits from the previous sequence. This method was repeated six times. The backward span scores were calculated by taking the mean of the last four reversal points. The BDS test's maximum score was used for analysis purposes (BDS maximum).

Reading Span Test. The RS test involved determining whether a Kannada statement was correct (secondary task) regarding meaning or logic while memorizing and recalling the bisyllabic words in Kannada (primary task) presented alternatively after each statement. Each trial had different types of primary and secondary tasks, so the participants could not estimate the difficulty level. It was investigated how accurately the participants completed the primary and secondary tasks. Each display in the RS task displayed a statement that either was meaningful or was not meaningful, followed by a CV syllabic word. (e.g., Naukaranige varʃad̪alli eradu baːri maːt̪ra katʃɛːrige ho:galu anumat̪i ni:ɖala:gut̪t̪ad̪e followed by /tʃa:ku//). Half of the statements in the test were meaningful, while the other half were meaningless and were presented randomly. The subjects responded by saying correct or incorrect. Each trial featured two to five sentences and bisyllabic word items. Three trials of each length were presented, making around 12 trials. An example set of stimuli from the reading span test is shown in Figure 1.

Figure 1. *An Example of a Stimulus Used in the Reading Span Test.*



Following the presentation of all trial items, the subject was asked to recollect every word after each sentence in the order in which they occurred. Participants were tested on their ability to remember all words correctly. The Reading Span Percent Correct Score Weighted (RS PCSW) measure was calculated. This measure sums together the elements that were recalled correctly, regardless of whether the items were perfectly recalled (and does not take serial order within items into account; Conway et al., 2005). A weighted score means that all the words will have similar weightage. If the word was recalled, it received a score of one; otherwise, it received a score of zero. The average of 12 trials yielded 12 values, divided by 12, which led to the RS PCSW score. The accuracy of the secondary task was also recorded, with a minimum of 85% needed as a criterion for the analysis of the RS PCSW score (Sanchez et al., 2010).

Results

The mean and standard deviation (*SD*) of age and four-frequency pure tone average (PTA) for 0.5, 1, 2, and 4 kHz were calculated using descriptive statistics. Independent *t*-tests revealed no significant differences between the pure tone threshold values of musicians and nonmusician groups at octave frequencies (from 250 Hz to 8 kHz) in each age group in both ears ($p > .05$). Reflexes were present at 500 Hz and 1000 Hz in both ears in nonmusician and musician groups across different age groups. OAEs were present in both groups and across different age groups, passing the 6 dB criteria for indicating their presence. Figures 2 and 3 show the mean and *SD* values for pure tone thresholds for the right and left ear, respectively, for musicians and nonmusicians.

Figure 2. *Mean and One SD (Error Bars) of Pure Tone Thresholds for Musicians and Nonmusicians for the Right Ear.*

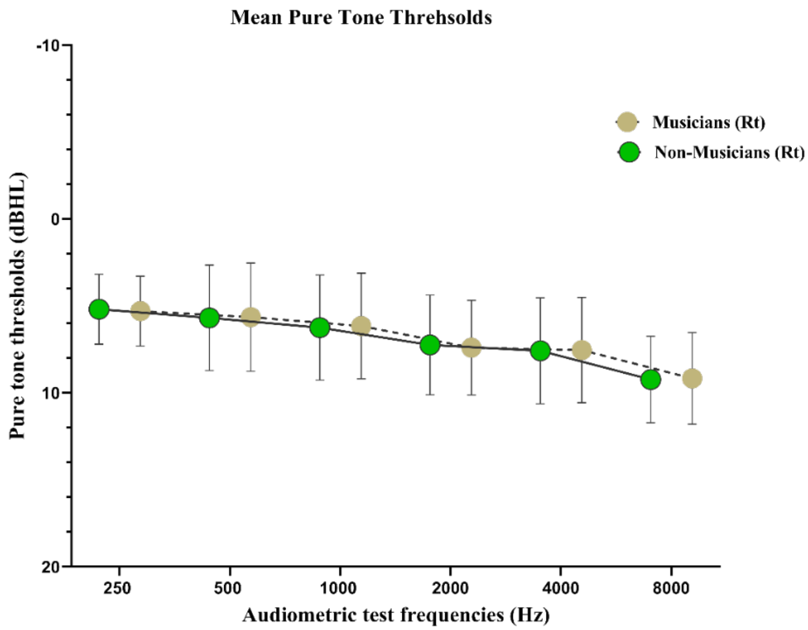
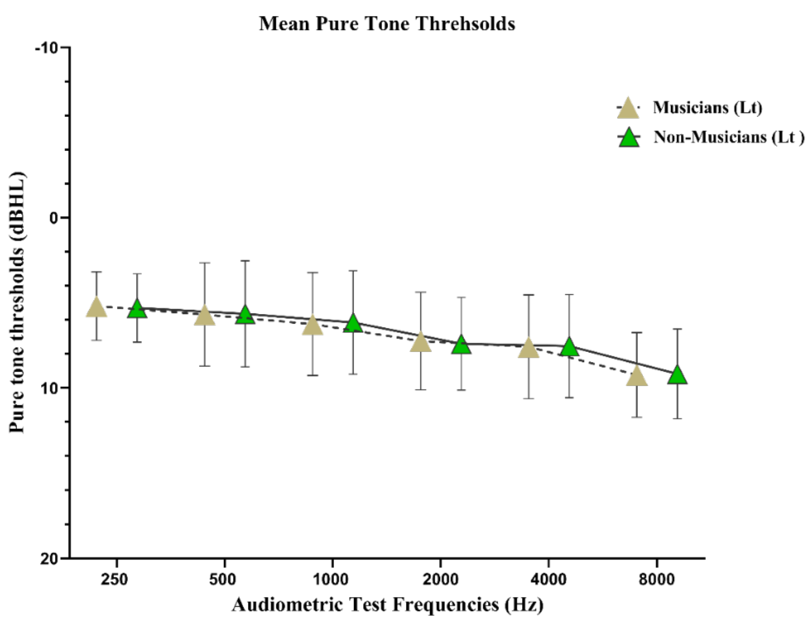


Figure 3. *Mean and One SD (Error Bars) of Pure Tone Thresholds for Musicians and Nonmusicians for the Left Ear.*



Similarly, descriptive statistics were performed to determine the mean and *SD* values of the dependent variables, namely the BDS maximum and RS PCSW scores. Shapiro Wilk's test of normality showed a bell-shaped distribution for all cognitive measures at different age groups (p > .05). Hence, parametric tests were used for statistical analyses. Figures 4 and 5 show the mean and *SD* values of BDS maximum and RS PCSW scores, respectively, for musicians and nonmusicians across different age groups.

Figure 4. *Mean and SD (Error Bars) for BDS Maximum Scores Across Different Age Groups in Musicians and Nonmusicians.*

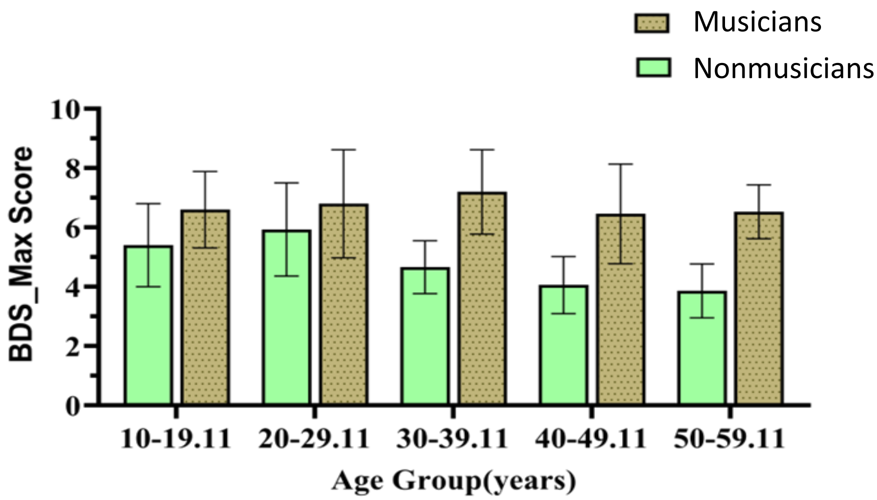
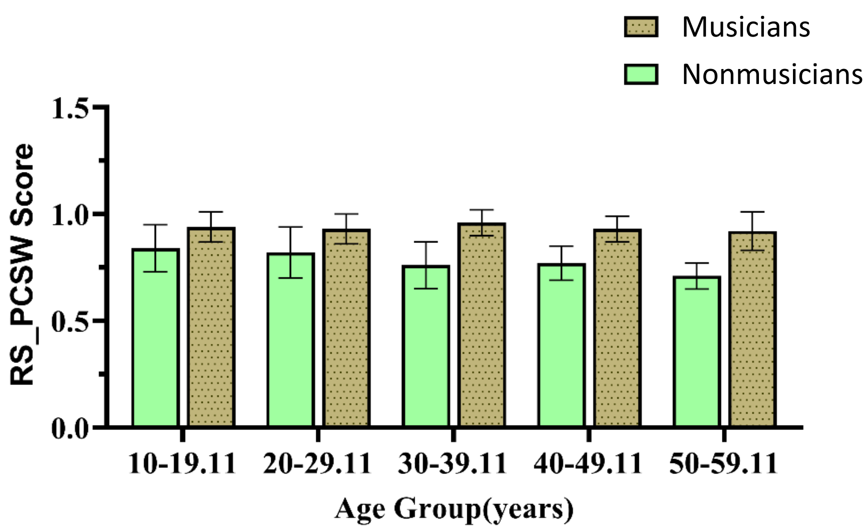


Figure 5. *Mean and SD (Error Bars) for RS PCSW Scores Across Different Age Groups in Musicians and Nonmusicians.*



Effect of Aging and Music Training on Auditory Cognitive Tests

Backward Digit Span Test. A two-way ANOVA (analysis of variance) was administered to assess the effects of aging and music training on BDS maximum score. Results of two-way ANOVA with musicianship and age group as the between-subject factors indicated that there was a significant musicianship effect, $F(1, 140) = 78.999$, $p = .001$, ηp2 = 0.361; there was a significant age effect, $F(4, 140) = 4.280$, $p = .003$, ηp2 = 0.109; and an interaction effect between musicianship and age effects, $F(4, 140) = 2.950$, $p = .022$, ηp2 = 0.078. The interaction effect is noted when the effect of one independent variable (musicianship) varies depending on the level of another independent variable (age groups). One-way ANOVA was conducted to resolve the interaction effects with age groups as the between-subject factor on nonmusicians and musicians. The test indicated a significant main effect of age groups in nonmusicians, $F(4, 70) = 8.179$, $p = .001$, ηp2 = 0.319. However, there was no significant age effect in musicians, $F(4, 70) = 0.613$, $p = .654$, ηp2 = 0.034. Independent *t*-tests were done to assess further the age effect noted in nonmusicians, and

Bonferroni's corrections were applied. Post-hoc analysis with Bonferroni's corrections for multiple comparisons indicated an effect of aging and its influence on test results only in nonmusicians. The impact of aging on this task initiates from 40–49.11 years in nonmusicians. However, there was no significant difference across different age groups among musicians. The outcomes are displayed in Table 1 below.

Table 1
Results of Independent t-Tests in Nonmusicians Across Different Age Groups on BDS Maximum Scores

Age Groups	*t* value	df	*p*-value
10–19.11 & 20–29.11	0.977	28	1.000
10–19.11 & 30–39.11	1.703	28	.500
10–19.11 & 40–49.11	3.035	28	.020
10–19.11 & 50–59.11	3.543	28	.005*
20–29.11 & 30–39.11	2.699	28	.06
20–29.11 & 40–49.11	3.910	28	.005*
20–29.11 & 50–59.11	4.384	28	< .001**
30–39.11 & 40–49.11	1.765	28	.44
30–39.11 & 50–59.11	2.414	28	.115
40–49.11 & 50–59.11	0.584	28	1.000

Note. df - degrees of freedom; *p* - significance level. *$p < .01$, **$p < .001$.

Reading Span Test. Results of two-way ANOVA with musicianship and age group as the between-subject factors indicated that on RS PCSW measure, a significant main effect of musicianship, $F(1, 140) = 116.760$, $p = .001$, ηp2 = 0.455, and an age effect, $F(4, 140) = 3.382$, $p = .011$, ηp2 = 0.088 were found; however, a significant interaction effect was not seen, $F(4, 140) = 2.320$, $p = .060$, ηp2 = 0.062. Since the interaction effect approached significance levels ($p = .060$), post-hoc analysis using one-way ANOVA was carried out across age groups to deconvolute the possible interaction effect. The test results revealed that there was a significant main effect of age groups in the nonmusician group, $F(4, 70) = 4.006$, $p = .006$, ηp2 = 0.186, whereas the same was not present in the musician group, $F(4, 70) = 0.705$, $p = .591$, ηp2 = 0.039. Age effects in nonmusicians were analyzed using independent *t*-tests. Bonferroni's corrections for multiple pair comparisons were used subsequently. The results suggested that aging degrades RS tasks only selectively in nonmusicians and that the age effects were evident in the 50–59.11-year-old age group. The outcomes are presented in Table 2 below.

A popular method to evaluate effect size in the context of ANOVA and other statistical tests is partial eta squared (ηp2). After adjusting for other variables, it shows the percentage of the dependent variable's overall variability that can be attributed to a specific independent variable (Cohen, 2013; Richardson, 2011). The current study indicated a "moderate to high" effect size (ηp2 = 0.062 to 0.455) on BDS maximum and RS PCSW measures, indicating the statistical significance of music training in improving cognitive capacities.

Table 2
Results of Independent T-Tests in Nonmusicians Across Different Age Groups on RS PCSW Scores

Age Groups	*t* value	df	*p*-value
10–19.11 & 20–29.11	0.357	28	1.000
10–19.11 & 30–39.11	1.875	28	.355
10–19.11 & 40–49.11	2.072	28	.24
10–19.11 & 50–59.11	3.810	28	.005*
20–29.11 & 30–39.11	1.436	28	.81
20–29.11 & 40–49.11	1.552	28	.66
20–29.11 & 50–59.11	3.158	28	.02
30–39.11 & 40–49.11	0.075	28	1.000
30–39.11 & 50–59.11	1.574	28	.635
40–49.11 & 50–59.11	2.041	28	.255

Note. df - degrees of freedom; *p* - significance level. **p* < .01, ***p* < .001.

Discussion

The results of the current study indicated that musicians showed a definite advantage compared to nonmusicians on WM tasks. Also, the process of aging occurs differently in musicians and nonmusicians. Musicians remain less affected by the degenerative effects of aging on cognition.

Effect of Aging and Music Training on Auditory Cognitive Tests

Backward Digit Span Test. Results indicated that musicians did not show the consequences of aging on the BDS maximum score. However, nonmusicians showed age effects at 40–49.11 years. BDS task assesses the complex verbal task that measures the maintenance and manipulation of memorized verbal information (Owen et al., 2005). According to an earlier study, only a slight difference was noted between musicians and nonmusicians in the BDS task compared to the forward span task, owing to the complexity of the task (Hansen et al., 2013). A former study by Lee et al. (2007) concluded that children with musical training performed better than those without musical training on simple maintenance tasks like forward digit span tasks compared to more complex functions like BDS. However, in our study, musicianship had a significant advantage on a complex verbal recall task like BDS.

Similar results of musician advantage on tasks of BDS have been reported previously in the literature, consistent with our findings, especially in adults (Zuk et al., 2014). A brief musical instrumental training program enhanced backward span performance but not forward span performance, according to Guo et al. (2018). Similar findings were discovered by Bergman Nutley et al. (2014), who showed that individuals and children with musical training fared better on BDS than their counterparts without training. BDS involves attending to the sequence of digits, forming auditory imagery and temporally sequencing the words and modifying them, similar to melody or rhythm imagery and imitation by musicians (Hansen et al., 2013). Playing or singing from memory emphasizes constantly sustaining and updating WM since it needs to match the music model stored in one's memory (Saarikivi et al., 2019). In an earlier study of WM assessment in musicians and nonmusicians, Talamini et al. (2016) found that musicians outperformed nonmusicians in their research unit of young people, regardless of the modality or complexity of digit span tasks, which is supportive of our study's results.

Reading Span Test. Results indicated that musicians did not show the effects of aging. However, nonmusicians showed age effects at 50–59.11 years. Franklin et al. (2008) compared musicians and nonmusicians to assess working and long-term memory on reading and operation span tasks. The study found that musicians outperformed nonmusicians in both tasks. The musicians in the current study might have used a sub-vocal rehearsal or sub-vocalization strategy to memorize the words, as reasoned in a similar prior study (Hansen et al., 2013). The current findings prove that verbal rehearsal mechanisms contribute to the verbal memory advantage associated with musical competence. Improved verbal memory may be due to better auditory cortex development (Helmbold et al., 2005), increased planum temporale volume, and left hemisphere activation in verbal memory tasks (Schlaug et al., 1995). Enhanced myelination and increased grey matter volume are also linked with improved WM task performance in musicians (Münte et al., 2002). Musicians process auditory stimuli more efficiently than nonmusicians (Tervaniemi et al., 2005). Similarly, with the RS task, superior performance in the audio-visual modality can be linked to the ability of the musically-trained brain to integrate information from different sensory modalities (Talamini et al., 2016). Additionally, music training may encourage chunking and other active learning strategies. Chunking is a strategy required to commit to a tune and transfer it to musicians' memory. Thus, musicians may outperform nonmusicians in WM tests using one or more such strategies (Talamini et al., 2017).

Conclusions

Music training can significantly slow the degenerative consequences of the aging process. Furthermore, our study found that music training increases cognitive capacities in people of various ages. Engaging in musical practice or giving music therapy may help to mitigate or reduce age-related cognitive losses (Maillard et al., 2023). Additionally, music instruction may also improve academic achievement in children and adolescents. This advantage may lead to improved job and career prospects once they reach maturity. Subjective outcomes must be correlated with objective test findings over a broad age range to encourage music learning and boost music-based rehabilitation, especially in the aging population.

Author Acknowledgment

The writers appreciate the permission given to perform the study by the Director of All India Institute of Speech and Hearing. The writers also want to thank all participants for participating and cooperating in this research.

Author Disclosure

Authors have no grants, financial interests, or conflicts to disclose.

References

Barrett, K. C., Ashley, R., Strait, D. L., & Kraus, N. (2013). Art and science: How musical training shapes the brain. *Frontiers in Psychology*, *4*, Article 713. https://doi.org/10.3389/fpsyg.2013.00713

Bergman Nutley, S., Darki, F., & Klingberg, T. (2014). Music practice is associated with development of working memory during childhood and adolescence. *Frontiers in Human Neuroscience, 7*, Article 926. https://doi.org/10.3389/fnhum.2013.00926

Boebinger, D., Evans, S., Rosen, S., Lima, C. F., Manly, T., & Scott, S. K. (2015). Musicians and non-musicians are equally adept at perceiving masked speech. *The Journal of the Acoustical Society of America, 137*(1), 378–387. https://doi.org/10.1121/1.4904537

Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound.* The MIT Press.

Chan, A. S., Ho, Y.-C., & Cheung, M.-C. (1998). Music training improves verbal memory. *Nature, 396*(6707), Article 128. https://doi.org/10.1038/24075

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Routledge. https://doi.org/10.4324/9780203771587

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review, 12*(5), 769–786. https://doi.org/10.3758/bf03196772

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*(3), 189–198. https://doi.org/10.1016/0022-3956(75)90026-6

Franklin, M. S., Sledge Moore, K., Yip, C. Y., Jonides, J., Rattray, K., & Moher, J. (2008). The effects of musical training on verbal memory. *Psychology of Music, 36*(3), 353–365. https://doi.org/10.1177/0305735607086044

Gaab, N., & Schlaug, G. (2003). The effect of musicianship on pitch memory in performance matched groups. *NeuroReport, 14*(18), 2291–2295. https://doi.org/10.1097/00001756-200312190-00001

George, E. M., & Coch, D. (2011). Music training and working memory: An ERP study. *Neuropsychologia, 49*(5), 1083–1094. https://doi.org/10.1016/j.neuropsychologia.2011.02.001

Gignac, G. E. (2015). The magical numbers 7 and 4 are resistant to the Flynn effect: No evidence for increases in forward or backward recall across 85 years of data. *Intelligence, 48*, 85–95. https://doi.org/10.1016/j.intell.2014.11.001

Gignac, G. E., & Weiss, L. G. (2015). Digit Span is (mostly) related linearly to general intelligence: Every extra bit of span counts. *Psychological Assessment, 27*(4), 1312–1323. https://doi.org/10.1037/pas0000105

Guo, X., Ohsawa, C., Suzuki, A., & Sekiyama, K. (2018). Improved digit span in children after a 6-week intervention of playing a musical instrument: An exploratory randomized controlled trial. *Frontiers in Psychology, 8*, Article 2303. https://doi.org/10.3389/fpsyg.2017.02303

Grassi, M., & Soranzo, A. (2009). MLP: A MATLAB toolbox for rapid and reliable auditory threshold estimation. *Behavior Research Methods, 41*(1), 20–28. https://doi.org/10.3758/BRM.41.1.20

Hansen, M., Wallentin, M., & Vuust, P. (2013). Working memory and musical competence of musicians and non-musicians. *Psychology of Music, 41*(6), 779–793. https://doi.org/10.1177/0305735612452186

Helmbold, N., Rammsayer, T., & Altenmüller, E. (2005). Differences in primary mental abilities between musicians and nonmusicians. *Journal of Individual Differences, 26*(2), 74–85. https://doi.org/10.1027/1614-0001.26.2.74

Houtgast, T., & Festen, J. M. (2008). On the auditory and cognitive functions that may explain an individual's elevation of the speech reception threshold in noise. *International Journal of Audiology, 47*(6), 287–295. https://doi.org/10.1080/14992020802127109

Howarth, A., & Shone, G. R. (2006). Ageing and the auditory system. *Postgraduate Medical Journal, 82*(965), 166–171. https://doi.org/10.1136/pgmj.2005.039388

Kraus, N., & Chandrasekaran, B. (2010). Music training for the development of auditory skills. *Nature Reviews Neuroscience, 11*(8), 599–605. https://doi.org/10.1038/nrn2882

Krishnaswamy, A. (2004). Inflexions and microtonality in South Indian classical music. *Frontiers of Research on Speech and Music*.

Kumar, A. U., & Sandeep, M. (2013). *Auditory cognitive training module*. ARF funded departmental project submitted to All India Institute of Speech and Hearing, Mysore.

Lee, Y.-S., Lu, M.-J., & Ko, H.-P. (2007). Effects of skill training on working memory capacity. *Learning and Instruction, 17*(3), 336–344. https://doi.org/10.1016/j.learninstruc.2007.02.010

Maillard, E., Joyal, M., Murray, M. M., & Tremblay, P. (2023). Are musical activities associated with enhanced speech perception in noise in adults? A systematic review and meta-analysis. *Current Research in Neurobiology, 4*, Article 100083. https://doi.org/10.1016/j.crneur.2023.100083

Martin, M., Zöllig, J., & Jäncke, L. (2009). The plastic human brain. *Restorative Neurology and Neuroscience, 27*(5), 521–538. https://doi.org/10.3233/RNN-2009-0519

Matysiak, O., Kroemeke, A., & Brzezicka, A. (2019). Working memory capacity as a predictor of cognitive training efficacy in the elderly population. *Frontiers in Aging Neuroscience, 11*, Article 126. https://doi.org/10.3389/fnagi.2019.00126

Mishra, S. K., Panda, M. R., & Herbert, C. (2014). Enhanced auditory temporal gap detection in listeners with musical training. *The Journal of the Acoustical Society of America, 136*(2), EL173–EL178. https://doi.org/10.1121/1.4890207

Muñoz-Pradas, R., Díaz-Palacios, M., Rodriguez-Martínez, E. I., & Gómez, C. M. (2021). Order of maturation of the components of the working memory from childhood to emerging adulthood. *Current Research in Behavioral Sciences, 2*, Article 100062. https://doi.org/10.1016/j.crbeha.2021.100062

Münte, T. F., Altenmüller, E., & Jäncke, L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews Neuroscience, 3*(6), 473–478. https://doi.org/10.1038/nrn843

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping, 25*(1), 46–59. https://doi.org/10.1002/hbm.20131

Pais, R., Ruano, L., P Carvalho, O., & Barros, H. (2020). Global cognitive impairment prevalence and incidence in community dwelling older adults—A systematic review. *Geriatrics (Basel, Switzerland), 5*(4), Article 84. https://doi.org/10.3390/geriatrics5040084

Reynolds, M. R., Niileksela, C. R., Gignac, G. E., & Sevillano, C. N. (2022). Working memory capacity development through childhood: A longitudinal analysis. *Developmental Psychology, 58*(7), 1254–1263. https://doi.org/10.1037/dev0001360

Richardson, J. T. E. (2011). Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review, 6*(2), 135–147. https://doi.org/10.1016/j.edurev.2010.12.001

Román-Caballero, R., Arnedo, M., Triviño, M., & Lupiáñez, J. (2018). Musical practice as an enhancer of cognitive function in healthy aging - A systematic review and meta-analysis. *PLoS ONE, 13*(11), Article e0207957. https://doi.org/10.1371/journal.pone.0207957

Saarikivi, K. A., Huotilainen, M., Tervaniemi, M., & Putkinen, V. (2019). Selectively enhanced development of working memory in musically trained children and adolescents. *Frontiers in Integrative Neuroscience, 13*, Article 62. https://doi.org/10.3389/fnint.2019.00062

Sanchez, C. A., Wiley, J., Miura, T. K., Colflesh, G. J. H., Ricks, T. R., Jensen, M. S., & Conway, A. R. A. (2010). Assessing working memory capacity in a non-native language. *Learning and Individual Differences, 20*(5), 488–493. https://doi.org/10.1016/j.lindif.2010.04.001

Schellenberg, E. G. (2006). Long-term positive associations between music lessons and IQ. *Journal of Educational Psychology, 98*(2), 457–468. https://doi.org/10.1037/0022-0663.98.2.457

Schlaug, G., Jäncke, L., Huang, Y., & Steinmetz, H. (1995). In vivo evidence of structural brain asymmetry in musicians. *Science (New York, N.Y.), 267*(5198), 699–701. https://doi.org/10.1126/science.7839149

Sluzenski, J., Newcombe, N. S., & Kovacs, S. L. (2006). Binding, relational memory, and recall of naturalistic events: A developmental perspective. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(1), 89–100. https://doi.org/10.1037/0278-7393.32.1.89

Talamini, F., Altoè, G., Carretti, B., & Grassi, M. (2017). Musicians have better memory than nonmusicians: A meta-analysis. *PLoS ONE, 12*(10), Article e0186773. https://doi.org/10.1371/journal.pone.0186773

Talamini, F., Carretti, B., & Grassi, M. (2016). The working memory of musicians and nonmusicians. *Music Perception: An Interdisciplinary Journal, 34*(2), 183–191. https://doi.org/10.1525/MP.2016.34.2.183

Tervaniemi, M., Just, V., Koelsch, S., Widmann, A., & Schröger, E. (2005). Pitch discrimination accuracy in musicians vs nonmusicians: An event-related potential and behavioral study. *Experimental Brain Research, 161*(1), 1–10. https://doi.org/10.1007/s00221-004-2044-5

Vaidyanath, R., & Yathiraj, A. (2014). Screening checklist for auditory processing in adults (SCAP-A): Development and preliminary findings. *Journal of Hearing Science, 4*(1), 27–37. https://doi.org/10.17430/890788

Venkatesan, S., & Basavaraj, V. (2009). *Ethical guidelines for bio-behavioral research involving human subjects, 1–23*. Mysore, India: All India Institute of Speech & Hearing. https://www.aiishmysore.in/en/pdf/ethical_guidelines.pdf

Vuontela, V., Steenari, M.-R., Carlson, S., Koivisto, J., Fjällberg, M., & Aronen, E. T. (2003). Audiospatial and visuospatial working memory in 6-13 year old school children. *Learning & Memory (Cold Spring Harbor, N.Y.), 10*(1), 74–81. https://doi.org/10.1101/lm.53503

Yathiraj, A., & Vanaja, C. S. (2015). Age related changes in auditory processes in children aged 6 to 10 years. *International Journal of Pediatric Otorhinolaryngology, 79*(8), 1224–1234. https://doi.org/10.1016/j.ijporl.2015.05.018

Zuk, J., Benjamin, C., Kenyon, A., & Gaab, N. (2014). Behavioral and neural correlates of executive functioning in musicians and nonmusicians. *PLoS ONE, 9*(6), Article e99868. https://doi.org/10.1371/journal.pone.0099868

Received: August 29, 2024
Accepted: September 17, 2024
Published: March 24, 2025

NeuroRegulation

EEG Signatures of Resilience Across Individuals With High and Low Anxiety

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Abstract

Background. Over the past decade, psychological resilience has become a key focus in psychological science. However, most research relies on self-report and psychosocial assessments to explore resilience across different populations and contexts. **Methods.** This two-phased study examined resilience using self-reported measures and EEG recordings. Phase 1 involved a cross-sectional analysis of resilience and anxiety in young adults using correlation and regression analysis. Phase 2 utilized a grouped experimental design with EEG resting-state recordings to compare high- and low-resilience individuals. EEG data were collected using a 64-channel Geodesic Sensor Net, NetAmps 400 Amplifiers, and NetStation Acquisition 5.0 Software. Spectral analysis was performed for group comparisons. **Results.** Significant EEG differences emerged between high- and low-resilience groups in the anterior midline, right frontal, right central, left parietal, and right parietal regions. Alpha band differences were predominantly frontal and right-sided, while beta band differences were posterior and left-sided. **Conclusions.** Results of the two phased study bridge the gap between psychosocial measures and electrophysiological measures in the study of resilience and anxiety. A conceptual model based on the findings is outlined to guide future research to investigate the mechanism between resilience and clinical presentations of anxiety and/or depression at the psychosocial and electrophysiological level.

Keywords: resilience; EEG; anxiety; neuropsychology; young adults

Citation: Gupta, S., & Reddy, J. (2025). EEG signatures of resilience across individuals with high and low anxiety. *NeuroRegulation, 12*(1), 12–28. https://doi.org/10.15540/nr.12.1.12

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Introduction

Psychological science has examined cognitive, emotional, psychosocial, and behavioral indices of response to stress or adversity for nearly four decades to grapple with the question of what makes individuals successfully cope with and overcome many adversities across their lifetime (Southwick & Charney, 2018). Stress and anxiety in adulthood is detrimental to happiness and optimal functioning (Joëls et al., 2007). Stress is a condition or set of conditions that perturbs the psychological and physiological balance of the individual compromising homeostasis (Franklin et al., 2012). Psychological resilience is the individual's ability to engage metacognitive, emotional, behavioral resources to maintain a positive equilibrium and successfully adapt to adversity (Gupta & McCarthy, 2021; Prince-Embury, 2014). Simply put, collision with adversities in life causes significant stress and/or trauma and resilience is what helps one to adapt (Luthar et al., 2000).

Resilience has been extensively researched from behavioral and psychosocial perspectives (Bonanno, 2004; Bonanno & Diminich, 2013; Charney, 2004; Cicchetti, 2010; Feder et al., 2009; Holman, 2011; Masten, 2001). Evidence has identified states and protective factors associated with resilience (Fletcher & Sarkar, 2013). However, due to a lack of studies addressing both psychosocial and neuropsychological indices of resilience which constitutes a glaring gap in the knowledge base (Feder et al., 2009). From a psychobiological foundation, resilience, the dynamic process of responses to adversity, consists of short- and long-term responses that reduce allostatic load (Curtis & Cicchetti, 2007; Feder et al., 2009). Several anatomical loci and functional connectivity in specific networks of the brain have been highlighted as having a key role in stress resistance and/or vulnerability; for example, amygdala activation (Davidson & McEwen, 2012; Kim, 2011; Mahan & Ressler, 2012), the hippocamus-pituitary-adrenal (HPA) axis (de Kloet et al., 2005), the medial prefrontal cortex, and dorsal ralphe nucleus (Franklin et al., 2012).

There is only limited research using EEG and/or functional magnetic resonance imaging (fMRI) that examines the neuropsychological foundations of resilience in healthy populations. Waugh et al. (2008) using task-based fMRI found that, when facing threats, participants with high resilience had prolonged activity in the insula to only adverse stimuli; however, participants with low resilience had prolonged activity in the insula to neutral and adverse stimuli. This suggests that individuals with greater resilience effectively adjust emotional resources used based on the situation. Kim and Bell (2006) linked the development of regulatory behavior, a predictor of resilience, to frontal asymmetry. Resilience was positive correlated with left orbitofrontal cortex and right amygdala activation in fMRI when firefighters had a relaxation versus a trauma script, indicating emotional reactivity to stress plays a role in resilience (Reynaud et al., 2013). Kong et al. (2015) employed the regional homogeneity (ReHo) measure to explore neural correlates of trait resilience and discovered that higher ReHo in the anterior cingulate cortex (ACC) and the insula within salience network was associated with lowered trait resilience. The study, however, failed to find an association of resilience with other prefrontal cortex (PFC) regions such as the orbitofrontal cortex (OFC). Amyg-EFP-NF (amygdala activation guided neurofeedback training) reduces alexithymia and faster emotional Stroop indicating better resilience among soldiers (Keynan et al., 2019). This may be explained by the moderating influence of theta/beta ratio on the effects of stress on attention control biases (Putman et al., 2014). Using resting-state EEG measures from delta, alpha, and beta bands from healthy participants, Paban et al. (2019) have demonstrated a negative association between brain network flexibility and psychological resilience. A measure of autonomic response to emotion, the late positive potential (LPP) for negative pictures, was also reported to be negatively correlated with resilience, and this was seen to be driven primarily by optimism, a composite factor in resilience (Chen et al., 2018). However, a limitation of these studies is their focus on emotion processing. As such, except for Paban et al. (2019) who have examined flexibility of networks, no other study has examined if resilience affects the resting brain state in a holistic manner in order to generate markers of resilience.

This study uses the framework of the multisystem model of resilience (Liu et al., 2017) which conceptualizes psychological resilience to be comprised of three structures. First, the innermost layer (i.e., physiological and demographic profile); second, the intermediate layer (i.e., internal factors psychological makeup, personal experiences); and third, the outer later (i.e. external, environmental factors). However, except for a few studies (Kong et al., 2015; Paban et al., 2019; Reynaud et al., 2013; Waugh & Koster, 2015), none have focused solely on exploration of the biological component. To address this gap, we build upon extant evidence that hypothesized resilience to be linked to regions within the PFC ACC and medial PFC (mPFC; Liberzon & Sripada, 2007; Milad et al., 2009; Sekiguchi et al., 2015). The study is a two-staged study with psychosocial indices of resilience being confirmed in the sample before a pilot exploration of electrophysiological indices. In doing so, this study finds significance by combining self-reported psychosocial aspects of resilience with electrophysiological EEG markers to provide a holistic insight into psychological resilience. Resilience has an inverse relationship with anxiety in young adults (Chesak et al., 2019; Connor & Davidson, 2003; Roberts et al., 2021; Steinhardt & Dolbier, 2008), acting as a protective factor (Dray et al., 2017; Gupta & McCarthy, 2021, 2022; Shin & Choi, 2020; Song et al., 2021). Therefore, resilience to stress and anxiety provides fertile ground to investigate neural differences in resilience. Hence in the current study, the first phase measured resilience and anxiety levels and identified a group of individuals with high resilience–low anxiety and low resilience–high anxiety. Subsequently, a selected small sample from both groups underwent EEG recording with a 64-channel EEG system. This novel study reports on the relationship between resilience and anxiety and aims to formulate an understanding of an electrophysiological profile for a resilient individual and, in particular, seeks to establish markers in the EEG of individuals with high psychological resilience and low anxiety as compared to individuals with low psychological resilience and high anxiety.

Method

Recruitment and Screening (Phase 1)

Participants (*n* = 130) were recruited from population from young adults (Age_{range} = 18–24). For Phase 1 (i.e., screening phase), purposive multi-stage sampling was conducted to ensure equal distribution of males and females based on sampling criteria. Individuals with diagnosed mental health disorders, learning disabilities, or sensory or motor deficits were excluded from the study since the goal was to understand EEG signature of resilience in healthy adults. Individuals with formal training in muscle relaxation, biofeedback or neurofeedback, and yoga were excluded to control again extraneous variables, since they act as a protective factor against anxiety. The study was reviewed and approved by the CHRIST (Deemed to be University) Ethics Committee (CU-RECEC-8/19). Participants were briefed on the procedures of the study, voluntary withdrawal rights and data protection protocols. Informed consent was obtained.

Procedure

Purposive sampling was undertaken for Phase 1 screening. Participants (*n* = 130) were briefed on the aims and objectives of the study and informed consent was obtained in line with the American Psychological Association code of ethics for psychologists. Participants were provided physical copies of the informed consent, demographic details questionnaire, and psychometrics. Identifying information was anonymized prior to screening analysis to mitigate potential bias. Psychometric measures were used to screen for psychological resilience, perceived stress, and anxiety.

Measures

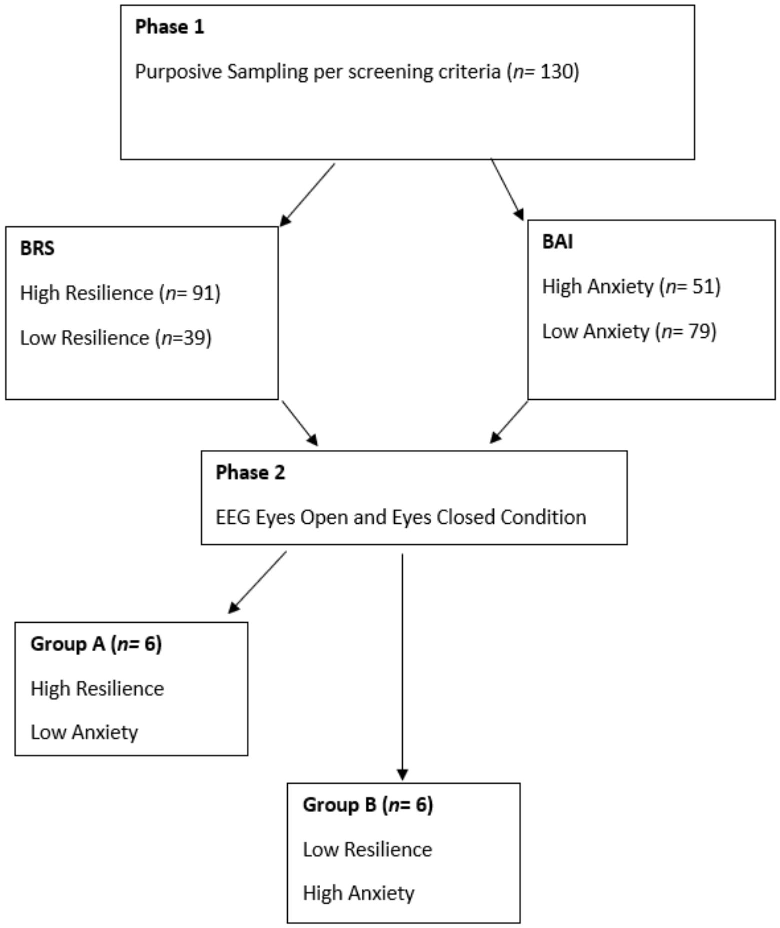
Brief Resilience Scale (BRS). The BRS developed by Smith et al. (2008) is a six-item measure of resilience to adapt and bounce back from stress and anxiety. BRS has been validated in young adults, cardiac patients, fibromyalgia, vocational rehabilitation adults, and among individuals with high anxiety and healthy controls (Jones et al., 2016; Kyriazos et al., 2018; Salah et al., 2021). It has adequate internal consistency across validation studies ranging from Cronbach's α of 0.71 to 0.91.

Perceived Stress Scale (PSS). PSS developed by Cohen et al. (1994) is a widely validated instrument that measures the perception to stress (i.e., the degree to which situations are appraised as stressful). Items are designed to tap into how unpredictable, uncontrollable, and overloaded respondents find their lives via their cognitive and affective responses. Review evidence highlights the PSS-10 item questionnaire used in this study has consistency internal reliability across multiple studies Cronbach's α greater than 0.70 (see Lee, 2012), which indicates adequate reliability.

Beck's Anxiety Inventory (BAI). BAI (Steer et al., 1990) consists of 21 items which closely represent symptoms of severe anxiety. It measures the following factors: subjective anxiety, neuropsychological arousal, autonomic arousal, and panic (Beck et al., 1991) and has a high internal reliability (Cronbach's α of 0.91) with a test–retest reliability of 0.75 (Beck et al., 1988). BAI has been evidence to be an effective screening measure of anxiety (Chapman et al., 2009; Leyfer et al., 2006) and has been used in nonclinical samples (Creamer et al., 1995).

Phase 1 Data Analysis. Data was scored according to the scoring instructions for each of the psychometric scales. Data was transferred to Microsoft Excel for sorting and scoring for Phase 1. Correlation and regression analysis was conducted using SPSS 20 to evaluate the relationship between resilience and anxiety in psychometric data obtained. In line with screening criteria, individuals at extreme valences scores of high resilience (4≥), high anxiety (30≥), low resilience (3≤), and low anxiety (21≤) were screened as eligible and were invited to participate in Phase 2 of the study. See Figure 1 for Phases of research.

Figure 1. *Procedural Research Phases Chart.*



Phase 2 Design and Participants

Study used an experimental design comparing EEG data of two groups on eyes-open and eyes-closed experimental conditions. Single-blind group assignment was conducted, and the EEG was recorded. Phase 1 screening rendered 30 potential participants meeting eligibility criteria. Potential participants were approached for voluntary participation in Phase 2 (i.e., EEG recording). Final study consisted of 12 study volunteers (18–24 years of age, 9 women and 3 men). Participants were assigned to groups in line with grouping criteria. Individuals with psychometric scores of high resilience and low anxiety were assigned to Group A. Individuals with psychometric scores of low resilience and high anxiety were assigned to Group B (see Table 1). The participants had no current or previous history of relevant physical illness (head injury, epilepsy) and they had not consumed any caffeinated beverage, drugs, or medication known to affect their EEG.

EEG Recording Sessions

The participants were seated comfortably in a dimly lit sound attenuated room. EEG data were recorded using a 64-channel Geodesic Sensor Net, NetAmps 400 Amplifiers, and NetStation Acquisition 5.0 Software (EGI, Inc., Eugene, OR). Scalp impedances were kept below 50 kΩ. The data was recorded as referenced to Cz with 250 Hz sampling rate. Data was viewed using 0.1 to 70 Hz band pass filter and a Notch filter at 50 Hz and monitored during the recording. All recordings were conducted in the afternoon (12:00 pm to 2:00 pm) or evening (4:00 pm to 6:00 pm). The participants were instructed to relax, and EEG was recorded for 3 min each for both eyes-open and eyes-closed conditions.

EEG Data Preprocessing and Editing

The data were imported offline into Matlab R2016b (The Matworks, Natick, MA, USA) environment using EEGLAB v 14.1.2b (Delorme & Makeig, 2004) and

Table 1
Demographic Information of Phase 2 Participants

Participant Code	Sex	Age	Electronic Devices (hr)	Handedness	Regular Exercise	Group	BRF	BAI
RE3006	F	21	3	88.25 (Right Handed)	YES	A	4.33	18
RE3034	M	24	3	100 (Right Handed)	NO	A	4.16	2
RE3001	F	22	4	100 (Right Handed)	NO	A	4.16	18
RE3003	F	20	5	100 (Right Handed)	YES	A	4	4
RE3004	F	21	2	100 (Right Handed)	NO	A	4.5	5
RE3005	F	21	8	100 (Right Handed)	NO	A	4.16	3
RE2007	F	19	3	100 (Right Handed)	YES	B	2.83	34
RE2006	F	21	4	100 (Right Handed)	YES	B	2.33	32
RE2002	F	19	5	100 (Right Handed)	YES	B	2.5	43
RE2005	F	21	5	100 (Right Handed)	NO	B	2.66	38
RE2004	F	20	3	100 (Right Handed)	YES	B	2	32
RE2003	M	18	5	100 (Right Handed)	NO	B	2.83	34

Note. RE3006, RE3033, RE3001, RE3003, RE3004, RE3005 are categorized as the high resilience group; and RE2007, RE2006, RE2002, RE2005, RE2004, RE2003 are classified as the low resilience group.

mffmatlabio2.02 (Pernet et al., 2019) importer for EGI files to preprocess the raw data. The data was first bandpass filtered between 0.1–45 Hz. Bad channels were identified after manual scanning of each file and subsequently these channels were excluded from the files. Hence, only some files did not contain data from F10, F9 and T9 channels. Eye electrode channels (61, 62, 63, and 64) were also excluded for all files.

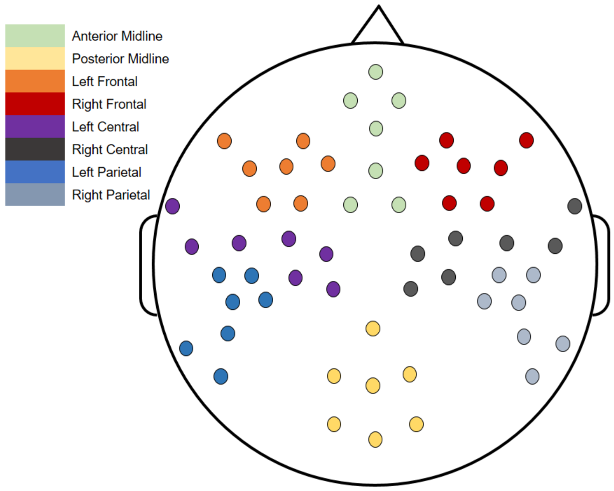
Next the data was segmented into 2-s epochs and the epochs with artifacts (eye blinks, EMG etc.) were rejected via visual inspection. All files with at least 90 s of good data were used. Four participants had only 46 s worth of good data for eyes-open condition. All data files were then rereferenced to average reference prior to the spectral analysis.

Spectral Analysis. Fast Fourier transform was applied using the Darbeliai plug-in (Baranauskas, 2009) for EEGLAB which uses the Welch's method to calculate FFT (window length = 1.996 s, no overlap). Absolute power was computed for all electrodes with good data for the following frequency bands: delta (1–3.5 Hz), theta (4–7.5 Hz), alpha1 (8–10 Hz), alpha2 (10–12 Hz), beta1 (13–15.5 Hz), beta2 (16–20.5 Hz), beta3 (21–30.5 Hz), and gamma (31–49.5 Hz). This was computed for both eyes-open and eyes-closed conditions.

Statistical Analysis. Absolute power data for both eyes-open and eyes-closed conditions was log transformed and subsequently analyzed for low anxiety versus high anxiety group differences using SPSS 20. For analysis, first log power data for each frequency band was aggregated into eight regional averages by grouping electrodes based on topographic contiguity. The regions were labelled as follows: anterior midline, posterior midline, left parietal, right parietal, left central, right central, left frontal, and right frontal (Figure 2). The regional averages were compared across groups (low resilience versus high resilience) using ANOVA.

Absolute power, in the eyes-open condition, for alpha1 (8–10 Hz) and alpha2 (10–12 Hz) for left frontal electrodes was subtracted from absolute power in the right frontal to create the frontal asymmetry score. Greater right frontal asymmetry values are positive and greater left frontal asymmetry values are negative.

Figure 2. *Head Plot Showing the Various Regional Electrode Groups.*



Note. Electrode grouping provided in Appendix A.

Ethical Considerations

Eligible participants for Phase 2 of the study were briefed on the EEG procedures and informed consent was obtained in line with the American Psychological Association code of ethics for psychologists. The study was reviewed and approved by the CHRIST (Deemed to be University) Ethics Committee (CU-RECEC-8/19). Participants were debriefed post-EEG recording. Identifying information such as legal name, address, and contact information data was anonymized with a participant code and stored in an encrypted drive with sole access for the research team in line with general data protection regulation (Voigt & von dem Bussche, 2017). Participants were informed of the voluntary nature of the study and their right to withdraw at any point.

Results

Phase 1 of the study aimed to assess the relationship between resilience and anxiety at obtained from psychometric self-report tests of the larger sample prescreening (n = 130). Shapiro-Wilk test of normality revealed data was not normally distributed (Resilience W = 0.026; Anxiety W = .000). Hence, Spearman's correlation was used, and results indicated a significant negative correlation between resilience and anxiety (r = −0.392, p < .01). Linear regression analysis indicated that increase in resilience significantly predicted a decrease in anxiety in this sample (β = −6.778, p < .01; see Table 2 below).

Table 2
Linear Regression Model Between Resilience and Anxiety in Phase 1 Sample (n = 130)

Predictor	Beta	t	R^2	ΔR^2	F	D-W
Resilience	−6.778	−4.800	0.154	0.147	23.038*	1.749

*p < .01.

Results (Phase 2)

From the subsample selected for EEG study, statistical analysis of EEG absolute power data from eyes-closed and eyes-open condition was conducted. ANOVA results revealed significant regional differences between the low resilience versus high resilience group only in the eyes-open EEG for high alpha and all beta bands (see Tables 3–5). Specifically, significant differences were identified between high resilience and low resilience groups in anterior midline region, $F(1, 10)$ = 5.031, p = .049); right frontal region $F(1, 10)$ = 5.715, p = .038); right central region, $F(1, 10)$ = 7.758, p = .019); left parietal region, $F(1, 10)$ = 6.660, p = .027); and right parietal region, $F(1, 10)$ = 5.440, p = .042). The difference in EEG Alpha band showed a strong frontal and a right-sided preponderance while the beta band findings were more posterior and left, when comparing between high and low psychological resilience group.

Table 4 shows the comparison of means for all eight frequency bands for the high and low resilience groups in eyes-open condition. This table shows higher power in high alpha and lower power in beta 3 band in some regions for the high resilience group, which was not reflected in ANOVA analysis, perhaps owing to a very small sample size and high variability. Specifically, in high alpha band in eyes-open condition, right frontal area displayed a difference with high resilience group showing higher activation (M = 11.25, SD = 13.62) compared to low resilience group (M = 1.94, SD = 0.65). Similar difference was found in anterior midline area with higher activation seen in high resilience group (M = 16.13, SD = 20.29) compared to low resilience group

Table 3
ANOVA Between High and Low Resilience Groups in High Alpha (10–12 Hz), Beta 1 (13–15.5 Hz), Beta 2 (16–20.5 Hz), and Beta 3 (21–30.5 Hz) Absolute Power

	High Alpha (10–12 Hz) Absolute Power		Beta 1 (13–15.5 Hz) Absolute Power		Beta 2 (16–20.5 Hz) Absolute Power		Beta 3 (21–30.5 Hz) Absolute Power	
Region	F	Sig	F	Sig	F	Sig	F	Sig
Anterior Midlines	5.031	0.049*	0.536	0.481	0.195	0.668	0.000	0.985
Left Frontal	3.489	0.091	0.172	0.687	0.077	0.787	0.083	0.779
Right Frontal	5.715	0.038*	0.442	0.521	0.088	0.773	0.357	0.563
Left Central	4.469	0.061	2.503	0.145	3.276	0.100	5.036	0.049*
Right Central	7.758	0.019*	1.071	0.325	1.548	0.242	0.367	0.558
Left Parietal	6.660	0.027*	5.577	0.040*	5.347	0.043*	8.094	0.017*
Right Parietal	5.440	0.042*	1.524	0.245	0.817	0.387	1.767	0.213
Posterior Midlines	4.008	0.073	1.328	0.276	1.312	2.279	6.443	0.029*

Table 4
Mean and Standard Deviation of All Frequency Bands From the Eyes-Open Condition

		Delta	Theta	Low Alpha	High Alpha	Beta1	Beta2	Beta3
Left Frontal	LR*	7.67 (1.81)^	3.13 (1.72)	2.94 (1.69)	1.93 (1.00)	0.81 (0.48)	2.48 (3.28)	4.94 (5.90)
	HR**	7.67 (2.65)	3.20 (1.18)	3.31 (1.68)	8.95 (10.30)	0.84 (0.28)	1.34 (0.56)	2.59 (0.68)
Right Frontal	LR	7.28 (1.53)	3.19 (1.65)	3.07 (1.66)	1.94 (0.69)	0.88 (0.36)	2.33 (1.87)	7.69 (10.07)
	HR	10.03 (2.93)	3.94 (1.40)	3.42 (1.61)	11.25 (13.62)	1.02 (0.38)	1.66 (0.83)	2.64 (0.95)
Anterior Midline	LR	6.15 (1.44)	4.16 (2.95)	4.28 (2.48)	2.83 (1.44)	0.78 (0.54)	1.11 (0.46)	1.93 (1.45)
	HR	6.30 (1.5)	4.32 (2.43)	4.81 (3.19)	16.13 (20.29)	0.89 (0.36)	1.31 (0.75)	1.76 (0.92)
Left Central	LR	4.26 (1.41)	2.58 (2.35)	2.85 (2.27)	2.12 (1.32)	0.66 (0.46)	0.94 (0.50)	1.36 (0.72)
	HR	5.41 (1.10)	3.11 (1.07)	3.31 (2.00)	8.22 (8.13)	0.96 (0.34)	1.67 (0.92)	2.81 (1.57)
Right Central	LR	4.93 (1.91)	3.00 (2.36)	3.07 (2.40)	1.97 (1.00)	0.80 (0.51)	1.11 (0.49)	1.86 (0.70)
	HR	5.51 (1.23)	3.46 (1.48)	3.50 (1.87)	9.41 (8.50)	0.99 (0.35)	1.66 (0.91)	2.28 (1.30)
Left Parietal	LR	4.18 (1.05)	2.96 (2.58)	3.51 (2.00)	2.38 (0.88)	0.69 (0.32)	0.98 (0.50)	1.34 (0.51)
	HR	6.05 (1.96)	3.94 (1.48)	5.70 (4.42)	21.09 (28.06)	1.55 (0.75)	2.38 (1.36)	3.77 (2.28)
Right Parietal	LR	4.59 (1.53)	3.05 (2.28)	5.12 (2.70)	3.74 (2.30)	0.82 (0.46)	1.20 (0.22)	1.46 (0.50)
	HR	4.97 (1.05)	3.39 (1.48)	6.74 (4.50)	16.28 (10.27)	1.26 (0.53)	1.92 (1.28)	2.54 (1.62)
Posterior Midline	LR	7.48 (1.85)	3.80 (2.13)	7.34 (3.92)	5.26 (2.86)	1.21 (1.00)	2.33 (1.87)	1.29 (0.47)
	HR	7.81 (2.34)	4.32 (2.43)	8.32 (5.96)	39.05 (50.58)	1.75 (1.05)	1.66 (0.83)	3.06 (1.85)

*LR = Low Resilience; **HR = High Resilience; ^ = Mean (*SD*).

(*M* = 2.83, *SD* = 1.44). High resilience group showed higher activation in right central (*M* = 9.41, *SD* = 8.50) and right parietal areas (*M* = 16.28, *SD* = 10.07). Hypothesis H2 stating differences between high and low resilience groups in alpha band and hypothesis H4 stating differences between high and low resilience groups in beta band stands supported.

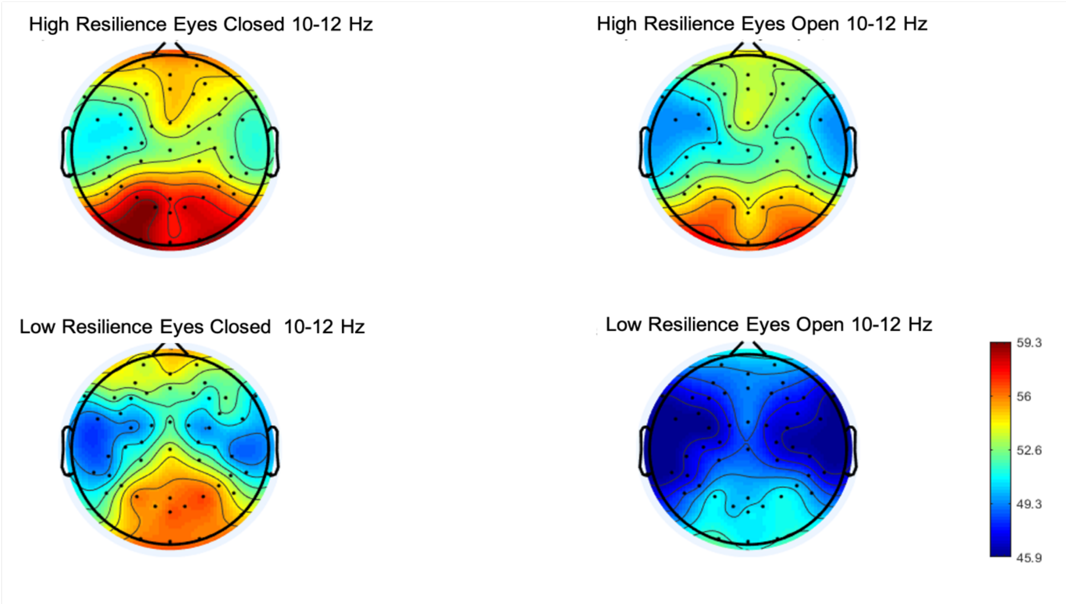
In eyes-closed condition (see Table 5), mean comparison of high resilience versus low resilience group revealed differences in the low alpha band A(8–10 Hz) in the left parietal area with high resilience group showing higher activation (*M* = 14.44, *SD* = 13.55) compared to low resilience group (*M* = 7.91, *SD* = 5.62). Many areas showed differences in high alpha band (10–12 Hz) between high resilience and low resilience groups. High resilience group showed higher activation of high alpha in right frontal (*M* = 14.65, *SD* = 13.60), anterior midline (*M* = 18.82, *SD* = 18.66), left central (*M* = 10.20, *SD* = 9.02), right central (*M* = 11.77, *SD* = 8.72), right parietal (*M* = 23.96, *SD* = 18.07), and posterior midline areas (*M* = 58.72, *SD* = 61.41). Therefore, hypothesis H3 stating differences between high and low resilience groups in delta band stands rejected.

Table 5
Mean and Standard Deviation of All Frequency Bands From the Eyes-Closed Condition

		Delta	Theta	Low Alpha	High Alpha	Beta1	Beta2	Beta3
Left Frontal	LR*	13.89 (5.53)^	5.49 (3.31)	6.84 (1.80)	5.43 (2.73)	3.16 (2.84)	2.78 (3.16)	3.16 (2.84)
	HR**	11.42 (2.05)	3.95 (1.40)	6.64 (4.29)	12.31 (12.19)	1.95 (0.66)	1.55 (0.79)	1.95 (0.66)
Right Frontal	LR	10.18 (3.38)	5.02 (2.98)	6.77 (1.78)	5.00 (2.22)	2.58 (1.69)	1.95 (1.33)	2.58 (1.69)
	HR	12.70 (4.66)	4.64 (1.54)	8.00 (4.94)	14.65 (13.60)	2.06 (0.77)	1.74 (0.84)	2.06 (0.77)
Anterior Midline	LR	9.48 (4.164)	6.09 (3.76)	9.96 (2.40)	7.62 (4.47)	1.69 (0.98)	1.67 (1.81)	1.69 (0.98)
	HR	10.31 (2.22)	5.36 (2.25)	11.66 (9.59)	18.82 (18.66)	1.78 (0.94)	1.77 (1.14)	1.78 (0.94)
Left Central	LR	7.75 (4.75)	4.87 (3.22)	5.71 (2.51)	4.09 (1.86)	1.69 (1.05)	1.45 (0.65)	1.69 (1.05)
	HR	6.34 (1.01)	3.90 (1.94)	6.20 (4.33)	10.20 (9.02)	2.18 (1.01)	1.74 (1.09)	2.18 (1.01)
Right Central	LR	8.92 (4.79)	5.90 (3.99)	6.25 (2.97)	4.30 (2.28)	1.89 (0.83)	1.49 (0.62)	1.89 (0.83)
	HR	7.06 (1.29)	4.41 (2.10)	7.32 (4.58)	11.77 (8.72)	2.14 (1.35)	1.95 (1.18)	2.14 (1.35)
Left Parietal	LR	6.69 (2.91)	5.05 (2.97)	7.91 (2.62)	5.09 (2.08)	1.80 (0.92)	1.59 (0.56)	1.80 (0.92)
	HR	8.79 (3.53)	5.80 (3.39)	14.44 (13.55)	25.02 (25.41)	3.42 (1.98)	3.14 (2.23)	3.42 (1.98)
Right Parietal	LR	8.39 (5.23)	6.37 (4.27)	14.99 (8.66)	9.85 (6.70)	1.72 (0.62)	1.87 (0.34)	1.72 (0.62)
	HR	7.78 (2.91)	5.32 (3.39)	14.70 (11.52)	23.96 (18.07)	2.44 (1.27)	2.59 (1.89)	2.44 (1.27)
Posterior Midline	LR	12.84 (7.28)	9.20 (6.23)	21.59 (6.74)	20.54 (14.87)	2.03 (1.08)	2.60 (1.22)	2.03 (1.08)
	HR	11.80 (5.99)	7.21 (5.43)	22.14 (17.73)	58.72 (61.41)	3.25 (1.81)	3.41 (2.57)	3.25 (1.81)

*LR = Low Resilience; **HR = High Resilience; ^ = Mean (*SD*).

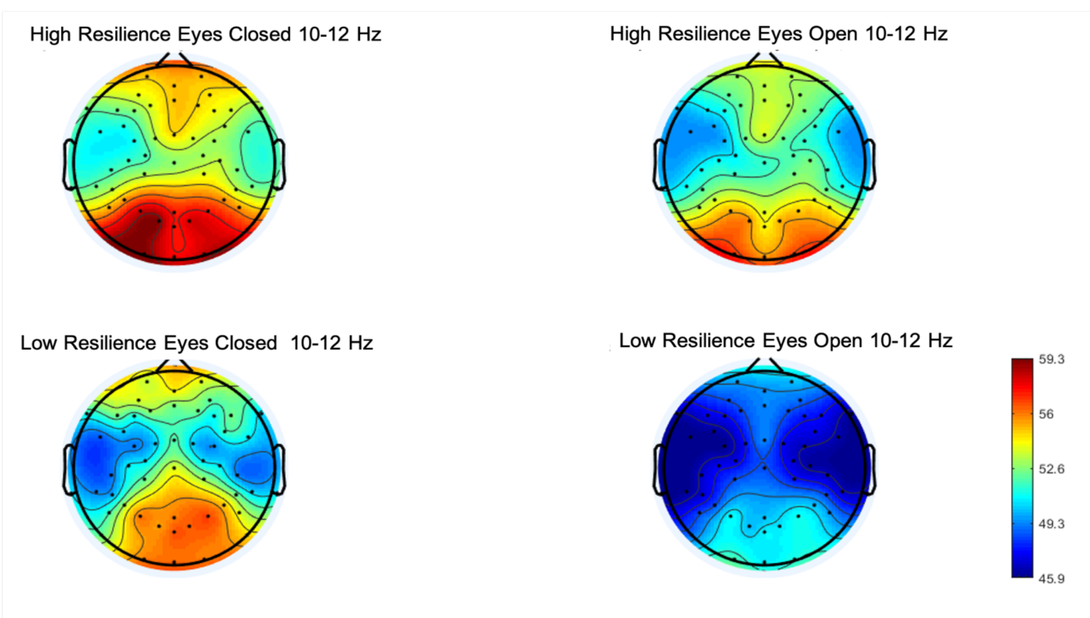
Figure 3. *Topographic Plots for High Alpha (10–12 Hz) Absolute Power.*



Note. Top row: Left - High Resilience Eyes Closed and Right - High Resilience Eyes Open.
Middle row: Left - Low Resilience Eyes Closed and Right - Low Resilience Anxiety Eyes Open.

Topographical plots indicate differences in neural activation between high resilience group and low resilience group in both eyes closed and eyes-open condition in high alpha band (10–12Hz; see Figure 3). Specifically, we observe differences in right and left frontal, orbitofrontal cortex, left and right parietal and right central areas in the eyes-closed condition. low resilience group shows minimal high alpha activity in eyes-open condition.

Figure 4. *Topographic Plots for Beta 3 (21–30.5 Hz) Absolute Power.*



Note. Top row: Left - High Resilience Eyes Closed and Right - High Resilience Eyes Open.
Middle row: Left - Low Resilience Eyes Closed and Right - Low Resilience Anxiety Eyes Open.

Table 6
Frontal Asymmetry Index in Alpha1 (8–10 Hz) and Alpha2 (10–12 Hz) Absolute Power

	Alpha1		Alpha2	
	LR	HR	LR	HR
Eyes Open	0.13	0.11	0.01	2.3
Eyes Closed	−0.07	1.36	−0.43	2.34

Note. LR = low resilience group; HR = high resilience group.

Topographical plots indicated marked differences in neural activation between high resilience group and low resilience group in both eyes-closed and eyes-open condition in beta 3 band (21–30.5 Hz; see Figure 4). In eyes-closed condition, differences between high and low resilience groups were observed in the left and right frontal, right central, and posterior midline areas. In eyes-open condition, low resilience group showed high activation in the left and right frontal areas in beta 3 band (21–30.5 Hz).

Frontal asymmetry index was computed as the difference of right minus the left hemisphere electrode values for six pairs of electrodes (AF4-AF3, F2-F1, F4-F3, F6-F5, F8-F7, F10-F9) and averaged to generate one measure for HR and LR. Positive values indicate greater right and negative values indicate a greater left balance. The analysis indicates high resilience group shows a stronger right frontal asymmetry in both eyes-open and eyes-closed condition in alpha 1 (8–10 Hz) and alpha 2 (10–12 Hz) bands. Low resilience group shows greater left frontal asymmetry in eyes closed condition in alpha 1 (8–10 Hz) and alpha 2 (10–12 Hz) bands.

Discussion

One of the results which evaluated the self-reported resilience and anxiety levels indicate a significant relationship between resilience and anxiety, with higher resilience inversely predicting anxiety in the regression model. The finding reflects extant literature across cultural contexts indicating resilience acts as a protective factor against anxiety (Jefferies et al., 2021; Song et al., 2021). Framing this finding with the multisystem model of resilience (Liu et al., 2017), this is the intermediate layer (i.e., internal factors psychological makeup, personal experiences) and outer later (i.e., external, environmental factors) of resilience. In selected participants for Phase 2 of the study, high resilience individuals reported low to moderate perceived stress and anxiety (see Table 1). This finds support in multiple types of evidence in literature which outlined how moderately stressful and anxiety-provoking events (perceived as tolerable) increase resilience levels often through stress inoculation, steeling, and anxiety-driven resilience (Cathomas et al., 2019; Crane et al., 2019; Dooley et al., 2017; Feder et al., 2019; Jefferies et al., 2021; Malhi et al., 2019).

Phase 2 study results indicate a robust difference in the scalp resting electrical patterns of high and low resilience groups (as measured by psychometric testing) in the eyes-open state as measured using noninvasive brain recordings (EEG) in eyes-open and eyes-closed condition (resting-states only). Our results indicate that high resilience group had greater high alpha band power in the right central, right and left parietal regions. High resilience group also had higher beta 3 power in left central, left parietal and posterior midline regions, suggesting a left and posterior preponderance. Functional neuroimaging studies associated with resilience are limited with most studies focused on clinical patient populations such as depression, trauma, PTSD, and anxiety disorder, where there are alterations present in emotion and stress regulation brain circuitry (van der Werff et al., 2013). Interestingly, our result suggesting resting-state changes may be in line with the findings of Kong et al. (2015) who reported that resilience has a significant negative correlation with rs-fMRI signals in bilateral insula, and rostral anterior cingulate cortex. The insula may be key to the resilience process due to its importance in human emotional processes (Uddin et al., 2017), while the ACC is linked to affect regulation (Stevens et al., 2011) which is a key component of resilience. Figure 5 below outlines a preliminary model on the operation of psychological resilience based on the findings of this pilot study and the trends highlighted during literature review.

Paban et al. (2019) used a dynamic network analysis of EEG data to identify key regions belonging to the "core functional network" outlined by van den Heuvel et al. (2009) as characteristics of high psychological resilience. This network includes regions involved in the cognitive processes of top-down attentional control (superior parietal cortex; Sestieri et al., 2017), decision-making in the OFC (Schuck et al., 2018) and cognitive-behavioral regulation (Bush et al., 2000) which oscillates in a fast-frequency beta band linked to reflect aspects of sensory information processes (Hong et al., 2008). Results from our study supports the conclusions drawn by Paban et al. (2019) indicating that high resilience group have higher beta activation in the left parietal, left central, and posterior midline regions. Topographical plots show a more frontal distribution of beta 3 (21–30 Hz) band (see Figure 4) also indicate regulated OFC and frontal cortex activation in beta 3 band (see Figure 4). Review evidence on the neurobiology of resilience have noted the importance of the PFC and limbic connection (Bolsinger et al., 2018; Feder et al., 2019; Holz et al., 2020; Ioannidis et al., 2020; Malhi et al., 2019). Activation of the PFC is crucial in cognitive and emotional inhibition, reducing amygdala reactivity to stressors and adversity. The findings of this preliminary pilot indicate that higher resilience individuals have greater prefrontal beta wave for cognitive and emotional regulation in response to stressors.

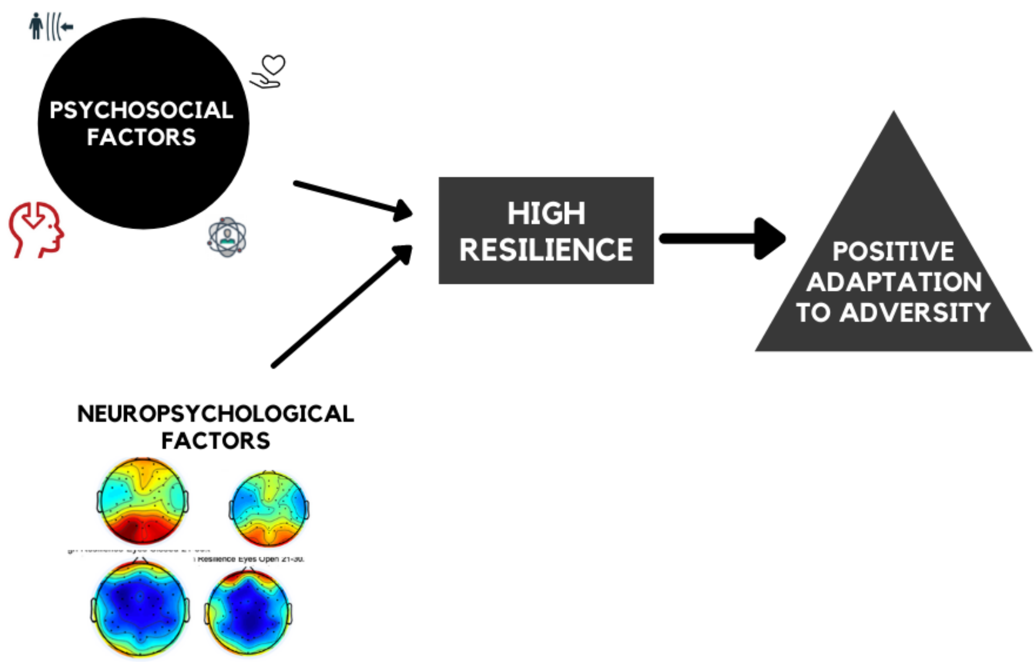
ANOVA results also indicate high resilience groups having greater activation in the right frontal, right central and parietal region in high alpha band and left central region in beta 3 band. The high alpha results have a right side and anterior preponderance while the beta 3 power results have a left posterior preponderance. High alpha band activation in the right frontal region is associated with less cognitive demands (Miyake et al., 2000). This could potentially point to the fact that high resilience individuals have lesser cognitive demands when responding to stressors and adversity. EEG resting state in high resilience children who had adapted to maltreatment, showed greater relative left central activity in the alpha band, in the eyes-open state (Curtis & Cicchetti, 2007). High and low resilience groups have also shown consistent differences over left parietal scalp regions in the high alpha, beta 1, beta 2, and beta 3 bands, with high resilience groups showing greater activation. A recent study (Kahl et al., 2020) found that greater resilience was associated with significant increase in cortical thickness in areas in right hemisphere cluster that included the lateral occipital cortex, the fusiform gyrus, the inferior parietal cortex, as well as the middle and inferior temporal cortex. The authors report that these anatomical areas are known to be involved in the processing of emotional visual input.

These findings provide support to models of adaptive regulation enhances resilience post adversity. Some examples are the coping circumplex model, systematic self-reflection model, cognitive appraisal of resilience, cognitive growth, and trajectory models (Bonanno et al., 2013; Crane et al., 2019; Stanisławski, 2019; Tedeschi & Calhoun, 2004; Yao & Hsieh, 2019). These models theorize aspects of cognitive flexibility in situational challenge appraisal, benefit finding, self-reflection, and regulation for resilient responses. Based on the findings of this study and review of literature, the interface between psychosocial and neuropsychological markers that contribute to high resilience are outlined in Figure 5 below.

A key driver of high resilience is the mastery motivation system which includes the ability to recall previous experiences where the individual overcame adversity resiliently (Masten, 2015). Our results indicate that the high resilience group shows higher beta 3 activation in the posterior midline region in addition to the higher left parietal activation. This region (specifically the lateral posterior parietal cortex and posterior midline region) has been linked to activation during demanding cognitive tasks and episodic memory retrieval (Daselaar et al., 2009). The combined findings highlight the importance of the psychological characteristics of resilience in addition to the neural markers indicating different brain region activation for high and low resilience individuals as theoretically underlined by Gupta (2021). Additionally, higher orbitofrontal, frontal, parietal, and central activations are a feature of the high resilience group. However, this activation merely indicates greater episodic retrieval of events and flexible cognitive reflections of it. The psychological makeup of the individual determines the nature of the episodic ruminations. They can be deliberate reflections which are structured thoughts to better understand the event and how to maximize mastery motivation to cope with event or it can lead to intrusive ruminations which lead to negative automatic thoughts and worries reinforced by past negative experiences which increases distress (Luca, 2019).

Results from the asymmetry analysis indicates high resilience group to have greater right frontal asymmetry in eyes-open and eyes-closed condition in the alpha 1 (8–10 Hz) band. This finding is in contrast to Curtis and Cicchetti's (2007) study on resilience related resting-state EEG differences

Figure 5. *Interface Between Psychosocial and Neuropsychological Markers Leading to High Resilience.*



where low resilience in children was associated with greater right alpha hemispherical activity in eyes-open condition. The findings of our study indicate that low resilience group has greater left frontal asymmetry in eyes-closed condition in alpha 1 (8–10 Hz) and alpha 2 (10–12 Hz) bands. The difference in findings of the current study and Curtis and Cicchetti (2007) can be linked to the eyes-open and eyes-closed conditions. Another explanation of the divergent results can be traced to the fact that self-reported anxiety was also a variable that may have played a role (e.g., low resilience group had high self-reported anxiety). Negative spontaneous mood (e.g., anxiety, perceived stress, tension) decreases when frontopolar activation asymmetry shifts to the right (Papousek & Schulter, 2002). Therefore, resilience individuals with greater right frontal activation not only self-report lesser anxiety and perceived stress but also have neural markers of the same. Greater right frontal activity reflects withdrawal related motivational states and traits of sadness (Coan & Allen, 2004), empathy (Tullet et al., 2012), with right-lateralized brain activity in the frontal region linked to the ability to exert sustained cognitive control (Ambrosini & Vallesi, 2016; Çiçek & Nalçacı, 2001). This is reflected at the psychosocial level where highly resilience individuals do show greater acceptance of negative emotions after adversity and can sustain cognitive control to facilitate adaptation (Hoorelbeke et al., 2016; Joorman et al., 2014). Wacker et al. (2010) found that greater right frontal asymmetry was associated with behavioural inhibition sensitivity during no-go trials on the go/no-go task which ties into the self-regulation ability that high resilience individuals have. In a 2003 experimental study with anger approach (fight) or anger-withdrawal (flight), Wacker et al. (2003) found that greater right frontal asymmetry was associated with fear-approach. This is supported by the fact that at the behavioral level, resilient individuals do not engage in avoidance coping when exposed to adversity or stressors (Campbell-Sills et al., 2006; Gupta & McCarthy, 2021). However, in-depth research is needed to explain this mechanism since other studies have linked increased rightward frontal alpha asymmetry to anxiety disorders and depression (Coan & Allen, 2004; Thibodeau et al., 2006).

Limitations

The sample size of Phase 2 of the current study is a limitation to generalizability as a pilot study. Data collection was initiated pre-COVID but had to be paused due to health and safety concerns. Participants' unavailability from Phase 1 screened sample led to the comparatively lesser sample size in group A and B. The limited source localization conducted in this study is another limitation which future research can address.

Future Directions

Future research can improve upon the sample size of this study and implement longitudinal designs with multistage EEG recordings. This would provide data into the stability of the EEG markers of resilience. There is also a need to distinguish between resilience and stress resistance (Fleshner et al., 2011). Future studies could conduct source localization to extend the precision of current findings. fMRI based designs could provide further insight into the EEG markers by testing the replicability of the regions associated with resilience in this study.

Author Acknowledgements

The authors would like to acknowledge Ms. Satya G. (Research Associate), for her invaluable support in the EEG recording and spectral analysis and the NeuroCognition Laboratory, Christ University, for the use of the EEG Facilities.

Author Disclosure

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. No artificial intelligence or generative AI was used during the study.

References

Ambrosini, E., & Vallesi, A. (2016). Asymmetry in prefrontal resting-state EEG spectral power underlies individual differences in phasic and sustained cognitive control. *NeuroImage, 124*(Part A), 843–857. https://doi.org/10.1016/j.neuroimage.2015.09.035

Baranauskas, M. C. C. (2009). Socially aware computing. In *ICECE 2009: VI International conference on engineering and computer education* (pp. 1–5).

Beck, A. T., Brown, G., Steer, R. A., & Weissman, A. N. (1991). Factor analysis of the Dysfunctional Attitude Scale in a clinical population. *Psychological Assessment: A Journal of Consulting and Clinical Psychology, 3*(3), 478–483. https://doi.org/10.1037/1040-3590.3.3.478

Beck, A. T., Steer, R. A., & Carbin, M. G. (1988). Psychometric properties of the Beck Depression Inventory: Twenty-five years of evaluation. *Clinical Psychology Review, 8*(1), 77–100. https://doi.org/10.1016/0272-7358(88)90050-5

Bolsinger, J., Seifritz, E., Kleim, B., & Manoliu, A. (2018). Neuroimaging correlates of resilience to traumatic events—A comprehensive review. *Frontiers in Psychiatry, 9*, Article 693. https://doi.org/10.3389/fpsyt.2018.00693

Bonanno, G. A. (2004). Loss, trauma, and human resilience: Have we underestimated the human capacity to thrive after extremely aversive events? *American Psychologist, 59*(1), 20–28. https://doi.org/10.1037/0003-066X.59.1.20

Bonanno, G. A., & Diminich, E. D. (2013). Annual research review: Positive adjustment to adversity—Trajectories of minimal–Impact resilience and emergent resilience. *Journal of Child Psychology and Psychiatry, 54*(4), 378–401. https://doi.org/10.1111/jcpp.12021

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences, 4*(6), 215–222. https://doi.org/10.1016/S1364-6613(00)01483-2

Campbell-Sills, L., Cohan, S. L., & Stein, M. B. (2006). Relationship of resilience to personality, coping, and psychiatric symptoms in young adults. *Behaviour Research and Therapy, 44*(4), 585–599. https://doi.org/10.1016/j.brat.2005.05.001

Cathomas, F., Murrough, J. W., Nestler, E. J., Han, M.-H., & Russo, S. J. (2019). Neurobiology of resilience: Interface between mind and body. *Biological Psychiatry, 86*(6), 410–420. https://doi.org/10.1016/j.biopsych.2019.04.011

Chapman, L. K., Williams, S. R., Mast, B. T., & Woodruff-Borden, J. (2009). A confirmatory factor analysis of the Beck Anxiety Inventory in African American and European American young adults. *Journal of Anxiety Disorders, 23*(3), 387–392. https://doi.org/10.1016/j.janxdis.2008.12.003

Charney, D. S. (2004). Psychobiological mechanisms of resilience and vulnerability: Implications for successful adaptation to extreme stress. *American Journal of Psychiatry, 161*, 195–216. https://doi.org/10.1176/appi.ajp.161.2.195

Chen, D., Wu, J., Yao, Z., Lei, K., Luo, Y., & Li, Z. (2018). Negative association between resilience and event-related potentials evoked by negative emotion. *Scientific Reports, 8*, Article 7149. https://doi.org/10.1038/s41598-018-25555-w

Chesak, S. S., Khalsa, T. K., Bhagra, A., Jenkins, S. M., Bauer, B. A., & Sood, A. (2019). Stress management and resiliency training for public school teachers and staff: A novel intervention to enhance resilience and positively impact student interactions. *Complementary Therapies in Clinical Practice, 37*, 32–38. https://doi.org/10.1016/j.ctcp.2019.08.001

Cicchetti, D. (2010). Resilience under conditions of extreme stress: A multilevel perspective. *World Psychiatry, 9*(3), 145–154. https://doi.org/10.1002/j.2051-5545.2010.tb00297.x

Çiçek, M., & Nalçacı, E. (2001). Interhemispheric asymmetry of EEG alpha activity at rest and during the Wisconsin Card Sorting Test: Relations with performance. *Biological Psychology, 58*(1), 75–88. https://doi.org/10.1016/S0301-0511(01)00103-X

Coan, J. A., & Allen, J. J. B. (2004). Frontal EEG asymmetry as a moderator and mediator of emotion. *Biological Psychology, 67*(1–2), 7–50. https://doi.org/10.1016/j.biopsycho.2004.03.002

Cohen, S., Kamarck, T., & Mermelstein, R. (1994). Perceived stress scale. *Measuring stress: A guide for health and social scientists, 10*(2), 1–2.

Connor, K. M., & Davidson, J. R. (2003). Development of a new resilience scale: The Connor-Davidson Resilience Scale (CD-RISC). *Depression and Anxiety, 18*(2), 76–82. https://doi.org/10.1002/da.10113

Crane, M. F., Searle, B. J., Kangas, M., & Nwiran, Y. (2019). How resilience is strengthened by exposure to stressors: The systematic self-reflection model of resilience strengthening. *Anxiety, Stress, & Coping, 32*(1), 1–17. https://doi.org/10.1080/10615806.2018.1506640

Creamer, M., Foran, J., & Bell, R. (1995). The Beck Anxiety Inventory in a non-clinical sample. *Behaviour Research and Therapy, 33*(4), 477–485. https://doi.org/10.1016/0005-7967(94)00082-U

Curtis, W. J., & Cicchetti, D. (2007). Emotion and resilience: A multilevel investigation of hemispheric electroencephalogram asymmetry and emotion regulation in maltreated and normally treated children. *Developmental Psychopathology, 19*(3), 811–840. https://doi.org/10.1017/S0954579407000405

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

Davidson, R. J., & McEwen, B. S. (2012). Social influences on neuroplasticity: Stress and interventions to promote well-being. *Nature Neuroscience, 15*(5)*,* 689–695. https://doi.org/10.1038/nn.3093

de Kloet, E. R., Joëls, M., & Holsboer, F. (2005). Stress and the brain: From adaptation to disease. *Nature Reviews Neuroscience, 6*(6), 463–475. https://doi.org/10.1038/nrn1683

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dooley, L. N., Slavich, G. M., Moreno, P. I., & Bower, J. E. (2017). Strength through adversity: Moderate lifetime stress exposure is associated with psychological resilience in breast cancer survivors. *Stress and Health, 33*(5), 549–557. https://doi.org/10.1002/smi.2739

Dray, J., Bowman, J., Campbell, E., Freund, M., Wolfenden, L., Hodder, R. K., McElwaine, K., Tremain, D., Bartlem, K., Bailey, J., Small, T., Palazzi, K., Oldmeadow, C., & Wiggers, J. (2017). Systematic review of universal resilience-focused interventions targeting child and adolescent mental health in the school setting. *Journal of the American Academy of Child & Adolescent Psychiatry, 56*(10), 813–824. https://doi.org/10.1016/j.jaac.2017.07.780

Feder, A., Fred-Torres, S., Southwick, S. M., & Charney, D. S. (2019). The biology of human resilience: Opportunities for enhancing resilience across the life span. *Biological Psychiatry, 86*(6), 443–453. https://doi.org/10.1016/j.biopsych.2019.07.012

Feder, A., Nestler, E. J., & Charney, D. S. (2009). Psychobiology and molecular genetics of resilience. *National Review Neuroscience, 10*(6)*,* 446–457. https://doi.org/10.1038/nrn2649

Fleshner, M., Maier, S. F., Lyons, D. M., & Raskind, M. A. (2011). The neurobiology of the stress-resistant brain. *Stress, 14*(5), 498–502. https://doi.org/10.3109/10253890.2011.596865

Fletcher, D., & Sarkar, M. (2013). Psychological resilience: A review and critique of definitions, concepts, and theory. *European Psychologist, 18*(1), 12–23. https://doi.org/10.1027/1016-9040/a000124

Franklin, T. B., Saab, B. J., & Mansuy, I. M. (2012). Neural mechanisms of stress resilience and vulnerability. *Neuron*, *75*(5), 747–761. https://doi.org/10.1016/j.neuron.2012.08.016

Gupta, S. (2021). Bouncing back! Clinical intersections of resilience, cognitive behavioural neuropsychology, and psychoneuroimmunology (PNI): An introduction. *Resilience, psychoneuroimmunology, neuropsychology: Applications in clinical settings.* Google Books.

Gupta, S., & McCarthy, P. J. (2021). Sporting resilience during COVID-19: What is the nature of this adversity and how are competitive elite athletes adapting? *Frontiers in Psychology, 12*, Article 611261. https://doi.org/10.3389/fpsyg.2021.611261

Gupta, S., & McCarthy, P. J. (2022). The sporting resilience model: A systematic review of resilience in sport performers. *Frontiers in Psychology, 13*, 1003053. https://doi.org/10.3389/fpsyg.2022.1003053

Holman, E. A., Lucas-Thompson, R. G., & Lu, T. (2011). Social constraints, genetic vulnerability, and mental health following collective stress. *Journal of Trauma and Stress, 24,* 497–505. https://doi.org/10.1002/jts.20671

Holz, N. E., Tost, H., & Meyer-Lindenberg, A. (2020). Resilience and the brain: A key role for regulatory circuits linked to social stress and support. *Molecular Psychiatry, 25*(2), 379–396. https://doi.org/10.1038/s41380-019-0551-9

Hong, L. E., Buchanan, R. W., Thaker, G. K., Shepard, P. D., & Summerfelt, A. (2008). Beta (~16 Hz) frequency neural oscillations mediate auditory sensory gating in humans. *Psychophysiology, 45*(2), 197–204 https://doi.org/10.1111/j.1469-8986.2007.00624.x

Hoorelbeke, K., Koster, E. H., Demeyer, I., Loeys, T., & Vanderhasselt, M.-A. (2016). Effects of cognitive control training on the dynamics of (mal)adaptive emotion regulation in daily life. *Emotion, 16*(7), 945. https://doi.org/10.1037/emo0000169

Ioannidis, K., Askelund, A. D., Kievit, R. A., & van Harmelen, A.-L. (2020). The complex neurobiology of resilient functioning after childhood maltreatment. *BMC Medicine, 18*(1), Article 32. https://doi.org/10.1186/s12916-020-1490-7

Jefferies, P., Höltge, J., & Ungar, M. (2021). Social anxiety and resilience: Associations vary by country and sex. *Adversity and Resilience Science, 2*(1), 51–62 https://doi.org/10.1007/s42844-020-00026-2

Joëls, M., Karst, H., Krugers, H. J., & Lucassen, P. J. (2007). Chronic stress: Implications for neuronal morphology, function, and neurogenesis. *Frontiers in Neuroendocrinology, 28*(2–3), 72–96. https://doi.org/10.1016/j.yfrne.2007.04.001

Jones, H. J., Stergiakouli, E., Tansey, K. E., Hubbard, L., Heron, J., Cannon, M., Holmans, P., Lewis, G., Linden, D. E. J., Jones, P. B., Davey Smith, G., O'Donovan, M. C., Owen, M. J., Walters, J. T., & Zammit, S. (2016). Phenotypic manifestation of genetic risk for schizophrenia during adolescence in the general population. *JAMA Psychiatry, 73*(3), 221–228. https://doi.org/10.1001/jamapsychiatry.2015.3058

Joormann, J., & Vanderlind, W. M. (2014). Emotion regulation in depression: The role of biased cognition and reduced cognitive control. *Clinical Psychological Science, 2*(4), 402–421 https://doi.org/10.1177%2F2167702614536163

Kahl, M., Wagner, G., de la Cruz, F., Köhler, S., & Schultz, C. C. (2020). Resilience and cortical thickness: A MRI study. *European Archives of Psychiatry and Clinical Neuroscience,* 270(5), 533–539. https://doi.org/10.1007/s00406-018-0963-6

Keynan, J. N., Cohen, A., Jackont, G., Green, N., Goldway, N., Davidov, A., Meir-Hasson, Y., Raz, G., Intrator, N., Fruchter, E., Ginat, K., Laska, E., Cavazza, M., & Hendler, T. (2019). Electrical fingerprint of the amygdala guides neurofeedback training for stress resilience. *Nature Human Behaviour, 3*(1), 63–73. https://doi.org/10.1038/s41562-018-0484-3

Kim, K. J., & Bell, M. A. (2006). Frontal EEG asymmetry and regulation during childhood. *Annals of the New York Academy of Sciences, 1094*(1), 308–312. https://doi.org/10.1196/annals.1376.040

Kim, M. J. Loucks, R. A., Palmer, A. L., Brown, A. C., Solomon, K. M., Marchante, A. N., & Whalen, P. J. (2011). The structural and functional connectivity of the amygdala: From normal emotion to pathological anxiety. *Behavioural Brain Research, 223*(2)*,* 403–410. https://doi.org/10.1016/j.bbr.2011.04.025

Kong, F., Hu, S., Wang, X., Song, Y., & Liu, J. (2015). Neural correlates of the happy life: The amplitude of spontaneous low frequency fluctuations predicts subjective well-being. *NeuroImage, 107,* 136–145. https://doi.org/10.1016/j.neuroimage.2014.11.033

Kyriazos, T. A., Stalikas, A., Prassa, K., Galanakis, M., Yotsidi, V., & Lakioti, A. (2018). Psychometric evidence of the Brief Resilience Scale (BRS) and modeling distinctiveness of resilience from depression and stress. *Psychology, 9*(7), 1828–1857. https://doi.org/10.4236/psych.2018.97107

Lee, E.-H. (2012). Review of the psychometric evidence of the perceived stress scale. *Asian Nursing Research, 6*(4), 121–127. https://doi.org/10.1016/j.anr.2012.08.004

Leyfer, O. T., Ruberg, J. L., & Woodruff-Borden, J. (2006). Examination of the utility of the Beck Anxiety Inventory and its factors as a screener for anxiety disorders. *Journal of Anxiety Disorders, 20*(4), 444–458. https://doi.org/10.1016/j.janxdis.2005.05.004

Liberzon I., & Sripada C. S. (2007). The functional neuroanatomy of PTSD: A critical review. *Progress in Brain Research, 167*, 151–169. https://doi.org/10.1016/S0079-6123(07)67011-3

Liu, J. J. W., Reed, M., & Girard, T. A. (2017). Advancing resilience: An integrative, multi-system model of resilience. *Personality and Individual Differences, 111*, 111–118. https://doi.org/10.1016/j.paid.2017.02.007

Luca, M. (2019). Maladaptive rumination as a transdiagnostic mediator of vulnerability and outcome in psychopathology. *Journal of Clinical Medicine, 8*(3), Article 314. https://doi.org/10.3390/jcm8030314

Luthar, S. S., Cicchetti, D., & Becker, B. (2000). Research on resilience: Response to commentaries. *Child Development, 71*(3), 573–575. https://doi.org/10.1111/1467-8624.00168

Mahan, A. L., & Ressler, K. J. (2012). Fear conditioning, synaptic plasticity and the amygdala: Implications for posttraumatic stress disorder. *Trends in Neuroscience, 35*(1)*,* 24–35. https://doi.org/10.1016/j.tins.2011.06.007

Malhi, G. S., Das, P., Bell, E., Mattingly, G., & Mannie, Z. (2019). Modelling resilience in adolescence and adversity: A novel framework to inform research and practice. *Translational Psychiatry, 9*(1), Article 316. https://doi.org/10.1038/s41398-019-0651-y

Masten, A. S. (2001). Ordinary magic. Resilience processes in development. *American Psychologist, 56*(3)*,* 227–238 https://doi.org/10.1037/0003-066X.56.3.227

Masten, A. S. (2015). *Ordinary magic: Resilience in development*. Guilford Publications.

Milad, M. R., Pitman, R. K., Ellis, C. B., Gold, A. L., Shin, L. M., Lasko, N. B., Zeidan, M. A., Handwerger, K., Orr, S. P., & Rauch, S. L. (2009). Neurobiological basis of failure to recall extinction memory in posttraumatic stress disorder. *Biological Psychiatry, 66*(12), 1075–1082. https://doi.org/10.1016/j.biopsych.2009.06.026

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Paban, V., Modolo, J., Mheich, A., & Hassan, M. (2019). Psychological resilience correlates with EEG source-space brain network flexibility. *Network Neuroscience, 3*(2), 539–550. https://doi.org/10.1162/netn_a_00079

Papousek, I., & Schulter, G. (2002) Covariations of EEG asymmetries and emotional states indicate that activity at frontopolar locations is particularly affected by state factors. *Psychophysiology, 39*(3), 350–360. https://doi.org/10.1017/S0048577201393083

Pernet, C. R., Appelhoff, S., Gorgolewski, K. J., Flandin, G., Phillips, C., Delorme, A., & Oostenveld, R. (2019). EEG-BIDS, an extension to the brain imaging data structure for electroencephalography. *Scientific Data, 6*(1), Article 103. https://doi.org/10.1038/s41597-019-0104-8

Prince-Embury, S. (2014). Three-factor model of personal resiliency and related interventions. In S. Prince-Embury & D. Saklofske (Eds.), *Resilience interventions for youth in diverse populations* (pp. 25–57). Springer. https://doi.org/10.1007/978-1-4939-0542-3_3

Putman, P., Verkuil, B., Arias-Garcia, E., Pantazi, I., & van Schie, C. (2014). EEG theta/beta ratio as a potential biomarker for attentional control and resilience against deleterious effects of stress on attention. *Cognitive, Affective, & Behavioral Neuroscience, 14*(2), 782–791. https://doi.org/10.3758/s13415-013-0238-7

Reynaud, E., Guedj, E., Souville, M., Trousselard, M., Zendjidjian, X., El Khoury-Malhame, M., Fakra, E., Nazarian, B., Blin, O., Canini, F., & Khalfa, S. (2013). Relationship between emotional experience and resilience: An fMRI study in firefighters. *Neuropsychologia, 51*(5), 845–849. https://doi.org/10.1016/j.neuropsychologia.2013.01.007

Roberts, N. J., McAloney-Kocaman, K., Lippiett, K., Ray, E., Welch, L., & Kelly, C. (2021). Levels of resilience, anxiety and depression in nurses working in respiratory clinical areas during the COVID pandemic. *Respiratory Medicine, 176*, Article 106219. https://doi.org/10.1016/j.rmed.2020.106219

Salah, H. M., Al'Aref, S. J., Khan, M. S., Al-Hawwas, M., Vallurupalli, S., Mehta, J. L., Mounsey, J. P., Greene, S. J., McGuire, D. K., Lopes, R. D., & Fudim, M. (2021). Effect of sodium-glucose cotransporter 2 inhibitors on cardiovascular and kidney outcomes—Systematic review and meta-analysis of randomized placebo-controlled trials. *American Heart Journal, 232*, 10–22. https://doi.org/10.1016/j.ahj.2020.10.064

Schuck, N. W., Wilson, R., & Niv, Y. (2018). A state representation for reinforcement learning and decision-making in the orbitofrontal cortex. In R. Morris, A. Bornstein, & A. Shenhav, *Goal-directed decision making* (pp. 259–278). Academic Press. https://doi.org/10.1016/B978-0-12-812098-9.00012-7

Sekiguchi, A., Kotozaki, Y., Sugiura, M., Nouchi, R., Takeuchi, H., Hanawa, S., Nakagawa, S., Miyauchi, C. M., Araki, T., Sakuma, A., Taki, Y., & Kawashima, R. (2015). Resilience after 3/11: Structural brain changes 1 year after the Japanese earthquake. *Molecular Psychiatry, 20*(5), 553–554. https://doi.org/10.1038/mp.2014.28

Sestieri, C., Shulman, G. L., & Corbetta, M. (2017). The contribution of the human posterior parietal cortex to episodic memory. *Nature Reviews Neuroscience, 18*(3), 183–192. https://doi.org/10.1038/nrn.2017.6

Shin, J. Y., & Choi, S. W. (2020). Interventions to promote caregiver resilience. *Current Opinion in Supportive and Palliative Care, 14*(1), 60–66. https://doi.org/10.1097/SPC.0000000000000481

Smith, B. W., Dalen, J., Wiggins, K., Tooley, E., Christopher, P., & Bernard, J. (2008). The brief resilience scale: Assessing the ability to bounce back. *International Journal of Behavioral Medicine, 15*(3), 194–200. https://doi.org/10.1080/10705500802222972

Song, J., Fogarty, K., Suk, R., & Gillen, M. (2021). Behavioral and mental health problems in adolescents with ADHD: Exploring the role of family resilience. *Journal of Affective Disorders, 294*, 450–458. https://doi.org/10.1016/j.jad.2021.07.073

Southwick, S. M., & Charney, D. S. (2018). *Resilience: The science of mastering life's greatest challenges*. Cambridge University Press.

Stanisławski, K. (2019). The coping circumplex model: An integrative model of the structure of coping with stress. *Frontiers in Psychology, 10*, Article 694. https://doi.org/10.3389/fpsyg.2019.00694

Steer, R. A., Scholl, T. O., & Beck, A. T. (1990). Revised Beck Depression Inventory scores of inner-city adolescents: Pre- and postpartum. *Psychological Reports, 66*(1), 315–320. https://doi.org/10.2466%2Fpr0.1990.66.1.315

Steinhardt, M., & Dolbier, C. (2008). Evaluation of a resilience intervention to enhance coping strategies and protective factors and decrease symptomatology. *Journal of American College Health, 56*(4), 445–453. https://doi.org/10.3200/JACH.56.44.445-454

Stevens, F. L., Hurley, R. A., & Taber, K. H. (2011). Anterior cingulate cortex: Unique role in cognition and emotion. *The Journal of Neuropsychiatry and Clinical Neurosciences, 23*(2), 121–125.

Tedeschi, R. G., & Calhoun, L. G. (2004). Posttraumatic growth: Conceptual foundations and empirical evidence. *Psychological Inquiry, 15*(1), 1–18. https://doi.org/10.1207/s15327965pli1501_01

Thibodeau, R., Jorgensen, R. S., & Kim, S. (2006). Depression, anxiety, and resting frontal EEG asymmetry: A meta-analytic review. *Journal of Abnormal Psychology, 115*, 715–729. https://doi.org/10.1037/0021-843x.115.4.715

Tullett, A. M., Harmon-Jones, E., & Inzlicht, M. (2012). Right frontal cortical asymmetry predicts empathic reactions: Support for a link between withdrawal motivation and empathy. *Psychophysiology, 49*(8), 1145–1153. https://doi.org/10.1111/j.1469-8986.2012.01395.x

Uddin, L. Q., Nomi, J. S., Hébert-Seropian, B., Ghaziri, J., & Boucher, O. (2017). Structure and function of the human insula. *Journal of Clinical Neurophysiology, 34*(4), 300–306. https://doi.org/10.1097/WNP.0000000000000377

van den Heuvel, M. P., Mandl, R. C., Kahn, R. S., & Hulshoff Pol, H. E. (2009). Functionally linked resting-state networks reflect the underlying structural connectivity architecture of the human brain. *Human Brain Mapping, 30*(10), 3127–3141. https://doi.org/10.1002/hbm.20737

van der Werff, S. J. A., van den Berg, S. M., Pannekoek, J. N., Elzinga, B. M., & van der Wee, N. J. (2013). Neuroimaging resilience to stress: A review. *Frontiers in Behavioral Neuroscience, 7*, Article 39. https://doi.org/10.3389/fnbeh.2013.00039

Voigt, P., & von dem Bussche, A. (2017). *The EU general data protection regulation (GDPR): A practical guide* (1st ed.). Springer International Publishing. https://doi.org/10.1007/978-3-319-57959-7

Wacker, J., Chavanon, M. L., Leue, A., & Stemmler, G. (2010). Trait BIS predicts alpha asymmetry and P300 in a Go/No-Go task. *European Journal of Personality, 24*(2), 85–105. https://doi.org/10.1002%2Fper.740

Wacker, J., Heldmann, M., & Stemmler, G. (2003). Separating emotion and motivational direction in fear and anger: Effects on frontal asymmetry. *Emotion, 3*(2), 167–193. https://doi.org/10.1037/1528-3542.3.2.167

Waugh, C. E., & Koster, E. H. W. (2015). A resilience framework for promoting stable remission from depression. *Clinical Psychology Review, 41*, 49–60. https://doi.org/10.1016/j.cpr.2014.05.004

Waugh, C. E., Wager, T. D., Fredrickson, B. L., Noll, D. C., & Taylor, S. F. (2008). The neural correlates of trait resilience when anticipating and recovering from threat. *Social Cognitive and Affective Neuroscience, 3*(4), 322–332. https://doi.org/10.1093/scan/nsn024

Yao, Z.-F., & Hsieh, S. (2019). Neurocognitive mechanism of human resilience: A conceptual framework and empirical review. *International Journal of Environmental Research and Public Health, 16*(24), Article 5123. https://doi.org/10.3390/ijerph16245123

Received: September 07, 2024
Accepted: October 14, 2024
Published: March 24, 2025

Appendix A

Figure 1A. *Electrode Grouping for the EGI 64-Channel Sensor Layout.*

Anterior Midline (AFz_A + F1_A + F2_A + Fz_A + FC1_A + FCz_A + FC2_A)/7.

Posterior Midline (Pz_A + PO3_A + POz_A + PO4_A + O1_A + Oz_A + O2_A)/7.

Left Parietal (LM_A + P9_A + P7_A + P5_A + TP7_A + CP5_A + P3_A)/7.

Right Parietal (RM_A + P10_A + P8_A + P6_A + TP8_A + CP6_A + P4_A)/7.

Left Central (CP1_A + C1_A + FC3_A + C3_A + C5_A + T7_A + T9_A)/7.

Right Central (CP2_A + C2_A + FC4_A + C4_A + C6_A + T8_A + T10_A)/7.

Left Frontal (AF3_A + F3_A + F5_A + FC5_A + FT7_A + F7_A + F9_A)/7.

Right Frontal (AF4_A + F4_A + F6_A + FC6_A + FT8_A + F8_A + F10_A)/7.

Montage used EGI 64-channel HydroCel Geodesic Sensor Net
(https://www.egi.com/research-division/geodesic-sensor-net

NeuroRegulation

Towards the Clinical Implementation of Noninvasive Brain Stimulation for Alleviating Social Communication Challenges: Input From Two Critical Stakeholder Groups

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Abstract

Introduction. Using noninvasive brain stimulation (NIBS) during social communication therapy significantly improves performance when compared to providing therapy alone. Speech-language pathologists (SLPs) have expertise and training in providing social communication therapy for individuals with social communication challenges, such as autistic individuals. **Methods.** Two studies were completed to gain input from stakeholders who will influence NIBS's path forward for clinical use in treating social communication challenges. Study 1 examined surveys from SLPs on the clinical implementation of NIBS. Study 2 examined surveys from autistic adults about their own personal experiences after completing a research study using NIBS. **Results.** The top concerns of SLPs for the clinical implementation of NIBS were focused on the availability of safety and efficacy research, access to training, and the cost of using NIBS. Autistic adults who had previously participated in a research study using NIBS reported no safety concerns but did report a desire to use NIBS again, especially if they could access it remotely through video supervision with a trained professional. **Conclusions.** The findings of these studies inform the future clinical implementation of NIBS for improving social communication therapy with individuals with social challenges, such as autistic individuals.

Keywords: noninvasive brain stimulation; transcranial direct current stimulation; social communication; autism spectrum disorder; speech-language pathology

Citation: Esse Wilson, J., Rafferty, M. B., Duran, G., Ortiz, A., & Tesche, C. D. (2025). Towards the clinical implementation of noninvasive brain stimulation for alleviating social communication challenges: Input from two critical stakeholder groups. *NeuroRegulation, 12*(1), 29–39. https://doi.org/10.15540/nr.12.1.29

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The past 2 decades have seen a sharp increase in research into the use of noninvasive brain stimulation (NIBS), such as transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS), to safely accelerate and/or enhance performance across many areas of cognitive performance including perception, mood, motor activities, and other cognitive functions (Antal et al., 2022; Mattioli et al., 2024). For example, in tDCS, weak, constant amplitude (direct) currents are delivered through electrodes placed on the scalp. Current flow between the electrodes that penetrates into the brain induces changes in local cortical excitability. In TMS, a brief pulse of current is induced to flow through a coil that is placed over the scalp. This stimulation can cause neuronal axons to fire, changing both local brain activity and activity at sites distant to the stimulation (for a review of tDCS/TMS, see Filmer et al., 2014). An attractive feature of NIBS is the ability to provide targeted treatment that focuses on specific brain processes to address each individual's challenges and needs, allowing for a personalized treatment approach. Importantly, tDCS units are also affordable, lightweight, portable, and safe, making their use attractive for clinical implementation in the field (Mondino et al., 2014).

While many NIBS devices are currently only available in investigational research settings, TMS has long been FDA-approved for clinical use in depression (Connolly et al., 2012). The FDA has also granted an investigational device exception (IDE) for a clinical trial utilizing an at-home based tDCS stimulation device in major depressive disorder (Soterix Medical Inc.), opening a path forward for future FDA approval and clinical implementation of NIBS for a wide variety of clinical disorders.

Speech-language pathologists (SLPs) have expertise and training in providing interventions that improve social communication, which encompasses language used in social contexts, social interaction, social cognition, and language processing—domains that are needed when one desires to share their experiences, thoughts, and emotions (American Speech-Language-Hearing Association, 2024a) SLPs must consistently seek to improve therapeutic effectiveness (American Speech-Language-Hearing Association, 2024b). Even if a treatment appears to work with a client, “we cannot afford, and our clients cannot afford, for therapy to be less efficient or effective than it might be given the state of research available to us” (Ratner, 2006, p. 258). While current social therapies may facilitate improved social communication, we and others have repeatedly shown that NIBS delivered during social communication therapy significantly improves social performance when compared to providing therapy alone (for a recent review and meta-analysis, see Liu et al., 2023). Specific improvements achieved through NIBS have been found for autistic individuals in many areas important to successful social communication and social interactions such as sociocognitive information processing (Chan et al., 2023), empathy and facial emotion recognition (Esse Wilson et al., 2021), emotion face processing and gaze behavior towards emotional faces (Qiao et al., 2020), social functioning and reduced restrictive, repetitive behaviors (Han et al., 2023), verbal emotion expression (Esse Wilson, Trumbo, et al., 2018), perspective taking and self-other processing (Martin et al., 2019) and social skills and sociability (Esse Wilson, Quinn, et al., 2018; Hadoush et al., 2020). Improvement of social communication is closely tied to quality of life (QoL) for individuals with autism spectrum disorder (ASD), especially autistic adults without a co-occurring intellectual disability who report a desire for improving their quality of relationships and social interactions (Camm-Crosbie et al., 2019) and their mental health that has been negatively impacted by high levels of loneliness (Schiltz et al., 2021). It is important to investigate paths forward for the clinical implementation of NIBS for improving social communication, including for individuals with ASD, where core diagnostic criteria include “persistent deficits in social communication and social interaction across multiple contexts” (American Psychiatric Association, 2013).

Currently available pharmacological and behavioral social supports often show only modest effects for alleviating social challenges. Additionally, current treatments may be associated with adverse and sometimes serious side effects (Aishworiya et al., 2022) and employ approaches that are not individualized (Klinger et al., 2021). Hence, the development of therapeutic supports demonstrating improved efficiency, effectiveness, and individualization is critically important for improving QoL for individuals facing social challenges, such as autistic adults.

Input is needed from important stakeholders, such as from autistic adults who have previously used NIBS, as well as from SLPs whose perceptions and beliefs about NIBS will greatly influence its path forward for clinical use. Thus, our investigation completed two studies: (a) examining the perceptions of SLPs on topics relevant to the clinical implementation of NIBS, and (b) investigating the perceptions of autistic adults who recently participated in research that utilized NIBS paired with social therapy. The rationale for completing this investigation is that results will inform the future clinical implementation of NIBS in SLP practice for use in improving social communication to improve QoL for individuals with social communication challenges, including autistic individuals.

Study 1

Methods

Survey and Participants. Study procedures were reviewed and approved by the New Mexico State University (NMSU) Institutional Review Board (IRB #2211026046). Study data were collected and managed using Research Electronic Data Capture (REDCap; Harris et al., 2009) software hosted at NMSU. Upon gaining access to the survey, participants read a brief consent statement and answered *yes* if they agreed to participate in the study (*no* if not). Of the 17 total survey questions, 11 were modeled after a previous survey of SLPs on the use of tDCS with aphasia (Keator et al., 2020). A total of 207 participants provided consent and completed surveys. The target participant population was licensed and certified SLPs (Clinical Fellow [CF] or Certificate of Clinical Competence [CCC]-SLPs). To evaluate the likelihood that the respondent was a CF or CCC-SLP, two questions were included in the survey for the purpose of evaluation by author Esse Wilson (an American Speech-Language Hearing Association [ASHA] certified and state licensed SLP) and author Duran (a 2nd-year masters-level graduate student). One evaluation question asked the respondent to provide a written answer describing the tool they would use to evaluate progress with clients with ASD. The second evaluation question asked the respondent to provide written text explaining why they thought more research studies have been completed on NIBS with individuals with aphasia than with autism. For both questions, a CF or CCC-SLP is expected to provide answers that demonstrate their training and qualifications. Responses to these two questions, along with the response to the question *What are your credentials?* were evaluated together. For example, surveys were disqualified from use in the study if a respondent answered "other" for their credentials and also wrote "I don't know" for either of the two evaluation questions. Both reviewers had 100% agreement that 21 surveys substantially departed from the answers a trained and qualified SLP would provide, and these surveys were removed from the final sample. Additionally, three surveys were removed as being incomplete. Twelve respondents reported being from countries outside the United States, six of whom did not report having CF or CCC-SLP and reported "other" as their credential. Given that certification requirements vary across countries, the survey responses of these six respondents were evaluated and determined to be reflective of responses that trained and qualified SLPs would provide. These six respondents were included in the final sample. Thus, surveys from a total of 184 respondents were included in the final sample. Participant professional characteristics gathered from the surveys are summarized in Table 1.

Table 1
Participant Professional Characteristics

Participant Characteristic	*N*	%
Years practicing as an SLP (mean = 18.0 years, range = 1–60 years)		
1–10 years	60	33
11–20 years	51	28
21–30 years	49	27
> 31 years	24	13
Credentials		
Masters CF-SLP	7	4
Masters CCC-SLP	140	76
Doctoral CCC-SLP	31	17
Other	6	3
Country where practicing		
United States (U.S.)	172	93
Canada	4	3
Other	8	4

Table 1
Participant Professional Characteristics

Participant Characteristic	*N*	%
SLP work setting (select all that apply)		
School-based	86	46
Private practice	53	28
Pre-K	49	26
University/higher ed.	42	23
Early intervention	36	19
Other	31	17
Hospital	18	10
Home visits	18	10
Adult outpatient	8	4

Note. Percentages yield greater than 100% accounted for by SLPs employed in more than one work setting. CF = clinical fellow, CCC = Certificate of Clinical Competence, SLP = speech-language pathologist.

Data Analysis

Quantitative Analysis. We first sought to characterize SLPs' existing familiarity with NIBS by constructing binary logistic regression models predicting participant responses to the question: *Before taking this survey, were you familiar with noninvasive brain stimulation, such as transcranial direct current stimulation (tDCS) or transcranial magnetic stimulation (TMS).* Models were built using the *glm* function in R's *stats* package (R Development Core Team, 2008). Our decision to use binary logistic regression was motivated by the dichotomous structure of the response data (Gardner et al., 1995). Separate models were created to predict the likelihood that participants had prior knowledge of NIBS on the basis of (a) work setting, (b) experience, and (c) current clinical involvement with ASD clients.

The experience model included factors for *Years of Clinical Experience* and *Clinician Credentials*. *Years of Experience* was treated as an ordinal factor, with each participant being assigned to one of four groups based on percentile rank. The groups consisted of those with less than 9 years of experience, those with 9–16 years of experience, those with 17–25 years of experience, and those with more than 25 years of experience. The group with less than 9 years of experience was treated as the reference level. The category of *Credentials* was also treated as an ordinal factor, with MS-CFY was treated as the reference level.

In addition to evaluating clinicians' familiarity with NIBS, we also sought to characterize clinicians' perceptions regarding the safety of NIBS. For this, we constructed binary logistic regression models to predict the likelihood that study participants agreed/disagreed with the statement: *I believe noninvasive brain stimulation (NIBS) is safe to use*. However, because this question permitted three types of responses (*yes, no, unsure*), we evaluated two separate classes of regression models. In the first, we evaluated which factors predicted increased likelihood that participants would select *yes* (i.e., the target response) as opposed to *no* or *unsure*, which were grouped together as nonaffirmative responses. In the second, we evaluated which factors predicted increased likelihood that participants would select the target response of *no* as opposed to *yes* or *unsure*, which were grouped together as non-oppositional responses. Within each model class, we constructed separate models to predict SLPs' perceptions of NIBS safety on the basis of (a) work setting, (b) experience, and (c) current clinical involvement with ASD clients.

Qualitative Analysis. Respondents were asked their concerns about incorporating NIBS, such as tDCS, into their practice and were offered choices for *safety, cost, administrative approval, reimbursement concerns, NIBS/tDCS training and education/continuing education, N/A I have no concerns,* and *other*. For respondents who chose *other*, they were asked to expand on their concerns by providing written comments. Authors Esse Wilson (an established researcher and SLP) and Ortiz (a 1st-year graduate student in speech-language pathology) independently evaluated the written answers by completing analysis based on Vaismoradi et al. (2016) including the phases of initialization and construction which involved reading transcriptions and noting meanings, coding, writing notes; classifying, comparing, and labeling repeating ideas that contribute to the study's questions; and defining and describing these ideas. After completion of the independent analyses, a discussion between the two evaluators was completed to determine final themes and their variations, as well as their connections to one another.

Results

Prior Familiarity With NIBS. (Answer options – *select one: yes, no*) Prior to taking the survey, 85 respondents (46.2%) reported being familiar with NIBS while 99 (53.8%) reported unfamiliarity. Prior familiarity with NIBS was significantly predicted by respondent work setting, years of experience as an SLP, and credentials. Working in a university setting (p = .002) or adult outpatient setting (p = .049) significantly predicted prior familiarity with NIBS. Additionally, prior familiarity significantly decreased with years of experience practicing as an SLP (p = .016). Specifically, prior familiarity was more likely to be reported in the group of respondents who had practiced fewer than 9 years and less likely in those with more than 9 years of experience. A marginally significant effect was observed for credentials, where those with the MS-CF and PhD-CCC (p = .077) were more likely to indicate prior familiarity than respondents with their MS-CCC.

Believe Safe to Use. (Answer options – *select one: yes, no, unknown*) The majority of respondents reported they did not know if NIBS was safe to use (n = 128, 69.6%), whereas 51 (27.7%) reported they believed it was safe to use, and 5 (2.7%) believed it was not safe to use. Believing NIBS is safe to use was significantly predicted by respondent work setting and experience. Specifically, adult outpatient SLPs (p = .048) were significantly more likely to select that NIBS is safe to use than the other possible responses. Additionally, SLPs with less years of experience were significantly more likely to believe NIBS is safe to use (p = .019).

Concerns About Incorporating NIBS Into Your Practice. (Answer options – *select all that apply: 1) safety, 2) cost, 3) administrative approval, 4) reimbursement concerns, 5) NIBS/tDCS training/continuing education, 6) N/A I have no concerns, 7) Other (please expand in the question that follows*)). The three highest concerns were: (a) safety 76% (n = 142), (b) NIBS/tDCS training and education/continuing education 66% (n = 122), and (c) cost 58% (n = 108). SLPs working in private practice (p = .007) or adult outpatient work settings (p = .057) or "other" setting (p = .004) were significantly more likely to indicate a concern about incorporating NIBS into practice due to reimbursement concerns. SLPs working in school-based (p = .087) or hospital (p = .078) work settings were marginally more likely to indicate a concern about incorporating NIBS into practice due to training and continuing education concerns.

Would Consider Using NIBS With My Clients With Autism Spectrum Disorder If. (Answer options – *select all that apply: 1) reasonably priced, 2) I were able to receive extensive training for it, 3) I could refer my client to another professional who was trained in using noninvasive brain stimulation, 4) research showed it was effective for helping my clients meet their goals, 5) research showed it was safe for use with my clients, or 6) I would not consider using noninvasive brain stimulation with my SLP clients.*) Observed as the three most important factors in considering the use of NIBS with autistic clients were: (a) research showed it was safe to use with clients (n = 145, 78%), (b) research showed it was effective for helping clients meet their goals (n = 142, 76%), and (c) SLPs were able to receive extensive training (n = 87, 47%) or could refer to another professional who was trained (n = 86, 46%). Price was also an important factor (n = 60, 32%).

Qualitative Analysis

Additional Concerns About Using NIBS. More than 30% (n = 56) of respondents reported they had additional concerns about incorporating NIBS into practice with their clients and provided written responses, from which four main themes emerged: (a) efficacy, (b) concerns about NIBS as a neuroaffirming treatment, (c) need for training/continuing education, and (d) need for treatment protocols. All comments were reviewed, with statements that reflected multiple respondents noted and provided as examples categorized by the four main themes, as shown in Table 2.

Table 2
Participant Example Statements (n = 56) by Theme From Question on Concerns About Incorporating NIBS Into Practice

Theme	Statements
Efficacy (*n* = 34)	• I want to see that it is evidence-based practice. • The amount and duration of research completed on what number of children and ages of children. • I don't think it is appropriate for school-based therapy.
Concerns about NIBS as a neuroaffirming treatment (*n* = 20)	• We should be working to affirm autistic people and not trying to make them neurotypical. • I do not believe that autism needs to be cured. • Despite reframing from neurodiversity, some children have extreme challenges resulting in self-injury and aggression. I would consider NIBS for these types of challenges.
Need for training/continuing education (*n* = 11)	• I would want to read the literature about NIBS and ASD. I need much more information.
Need for treatment protocols (*n* = 9)	• No existing protocols to match intervention to target specific areas of concern for clients with autism, given the spectrum of the disorder.

Study 2

Autistic adults without a co-occurring intellectual disability frequently possess unique gifts (Baron-Cohen, 2009; Happe & Vital, 2009) and a near 50% college completion rate (Rødgaard et al., 2022). Yet, many autistic adults continue to face social challenges that negatively impact their mental health (Schiltz et al., 2021), contribute to the lowest employment rate among disability groups (Roux et al., 2015), high rates of self-reported depression and anxiety (Ayres et al., 2018), and a desire for improved relationships and social interactions (Camm-Crosbie et al., 2019). Research into the use of NIBS has demonstrated success in alleviating social challenges (Esse Wilson et al., 2021), treating depression (Palm et al., 2012), and reducing anxiety (Zheng et al., 2024). However, any future clinical implementation of NIBS will require input from autistic adults who have themselves used NIBS. Thus, Study 2 is a survey of autistic adults who have previously participated in a research study that utilized NIBS (specifically tDCS) paired with simultaneous social learning activities.

Methods

Study and survey procedures were approved by the Office of the Institutional Review Board of the University of New Mexico (IRB #21814). Thirty-two autistic adults (adults diagnosed with ASD or having high traits of autism) without a co-occurring intellectual disability (as confirmed by the Shipley-2 test of intelligence) were contacted who had previously completed a research study that utilized tDCS. Of these 32 autistic adults, all had requested to be contacted in the future for studies. Fourteen respondents provided consent to participate and completed a 15-item email survey on their experiences with NIBS. Participants scored a 17 or higher on the autism quotient (AQ), a measure of one's level of autistic traits (Baron-Cohen et al., 2001). Additionally, the Autism Diagnostic Observation Schedule – Second Edition (ADOS-2; Lord et al., 2012) was administered. Participant characteristics are summarized in Table 3.

Participants provided their level of agreement or disagreement or each survey statement (1 = *definitely disagree*, 2 = *disagree*, 3 = *agree*, 4 = *definitely agree*).

Table 3
Participant Characteristics

Participant Characteristic	Range	Mean
Years of age	18–29	23
Shipley-2 standard scores	89–125	114
AQ scores	18–44	33
ADOS-2 categorization	autism (11), non-autism (but with high traits of autism) (2)	
Sex at birth	male (3), female (11)	

Note. Shipley-2 = Shipley second-edition, AQ = autism quotient, ADOS-2 = Autism Diagnostic Observation Schedule, Second Edition.

Results

Results were organized into four categories (a) *general NIBS topics*, (b) *autistic prioritized NIBS treatment*, (c) *development of NIBS treatment goals*, and (d) *NIBS for alleviating negative symptoms*.

General NIBS Topics. In response to *Had you heard of noninvasive brain stimulation before participating in a research study?* 93% replied *no* with 7% replying *yes.* For the question *During my research study, I felt NIBS was safe to use,* all respondents reported *agree* or *definitely agree.* For *NIBS is appealing to me as a possible alternative to other therapies, such as pharmaceuticals,* the majority of respondents replied with *agree* or *definitely agree,* with two replying with *disagree,* and the statement *It is important that people with autism play a role in the design phase of brain stimulation research that will treat negative symptoms of autism* was overwhelmingly answered with *definitely agree* with one respondent answering *agree.*

Delivery of NIBS. The majority of respondents chose *agree* or *definitely agree* in response to the question *If NIBS were available as a free or low-cost treatment to address negative symptoms of autism, I would seek this treatment,* with four respondents choosing *disagree*. In response to *I would be comfortable setting up and administering NIBS myself in my own home if a trained professional was assisting me through a video meeting,* the majority of respondents chose *agree* or *definitely agree* with one respondent replying with *disagree*, and for *I would only want to use noninvasive brain stimulation if it is administered by a trained professional when I visit them in their office* the overwhelming majority chose *disagree* with one respondent choosing *agree*.

***Autistic Prioritized NIBS Treatment*.** For the statement, *I would like trained professionals to work with me to develop treatment goals for using NIBS*, respondents were closely split three ways between *disagree, agree,* and *definitely agree*. For *I'd like to develop my own treatment goals for using NIBS* the majority responded with *agree* or *definitely agree,* with three respondents who replied with *disagree*. In response to the statement *Parents should be solely responsible for determining the NIBS treatment goals for their minor children* all respondents replied with *disagree* or *definitely disagree*. Last, in response to *Parents should work with highly trained professionals to determine NIBS treatment goals for their children* the majority of respondents replied *agree* or *definitely agree,* with two respondents providing *disagree*.

NIBS for Alleviating Negative Symptoms. For the statement *NIBS should be used to address negative symptoms of autism, not used to become what is considered closer to neurotypical,* the majority of respondents overwhelmingly replied with *definitely agree*, with four respondents replying with *agree*. In response to *Parents should pursue the use of NIBS to attempt making their child more neurotypical, if that is an option,* respondents overwhelmingly chose *disagree* or *definitely disagree,* with one respondent choosing *agree*. Last, in response to *Parents should pursue using NIBS to treat their child's negative symptoms of autism, but they should not pursue using it in an attempt to make their child more neurotypical,* the majority responded with *agree* or *definitely agree*, with three responding with *disagree*.

General Discussion

This is the first study to report on the perceptions of either SLPs or autistic adults on topics related to the clinical implementation of NIBS. To determine these perceptions, two studies were completed: (a) Study 1 which was an online survey of SLPs and (b) Study 2 which was an email survey of autistic adults who had recently participated in a research study that used NIBS paired with social therapy.

Study 1: SLPs

SLPs from diverse work settings with a broad range of years of experience were represented in the survey. Most SLPS reported practicing in the United States, nearly half reported at least one of their work settings was school-based, and most had the credentials of MS CCC-SLP. Of these respondents, more than half reported they had no familiarity with NIBS prior to taking the survey. Overall, SLP respondents reported similar perceptions and bconcerns for implementing NIBS into their practice with their clients with ASD, expressing top concerns for needing research demonstrating the safety and effectiveness of NIBS, training and continuing education for using NIBS, and the cost of using NIBS. These findings were at odds with recent literature that has widely reported on the safety, efficacy, and affordability of tDCS, in particular (Bikson et al., 2016; Sauvaget et al., 2019; Zheng et al., 2024). However, the high number of SLP respondents who reported having no prior knowledge of NIBS may explain their unfamiliarity with recent findings reporting safety, efficacy, and affordability. Regardless of their perceptions and concerns, 76% of SLP respondents reported they would use NIBS with their clients with ASD if it was safe, and even more (78%) reported they would use NIBS with the clients with ASD if it was effective in meeting client goals. These findings suggest the willingness of SLPs to seek novel evidence-based interventions to help their clients, as well as the critical importance of raising awareness among SLPs about the safety, efficacy, and affordability of NIBS, which will be necessary for future efforts to move research findings to clinical implementation.

Additionally, future studies would benefit from the addition of survey questions that address perceptions of SLPs on NIBS use with autistic children separately from adults, as several of our findings results suggest SLPs have different perceptions for using NIBS with children versus adults.

Concerns were also expressed in the qualitative analysis about whether NIBS is a neuroaffirming treatment (*n* = 20, 11% of total respondents). Autistic adults without a co-occurring intellectual disability (approximately 44% of individuals in the United States [Maenner et al., 2023]) are positioned to engage in self-advocacy and make decisions about their own care (Leadbitter et al., 2021), which may include choosing to help researchers during the design phase of a study or participating in studies utilizing NIBS. An interest in self-advocacy may explain why all of the autistic adults who completed the NIBS research study requested to be contacted for future studies.

It was revealed through qualitative analysis of SLP comments that many respondents were viewing NIBS primarily through the lens of its use with children (e.g., "I don't think it is appropriate for school-based therapy", "… some children have extreme challenges", "… the amount and duration of research completed on what number of children and ages of children"). This view may be explained by the high number of respondents who reported that at least one of their work settings involved working with children (early intervention, pre-K, or school-based). However, these responses highlight a need for a continued effort to raise awareness about the safety and efficacy of using NIBS with children, including children with ASD (Romei et al., 2019).

Study 2: Autistic Adults

Although most autistic adult respondents (93%) reported having no familiarity with NIBS prior to participating in the study, all respondents reported they either *agree* or *definitely agree* that NIBS felt safe to use during their study. Autistic adults overwhelmingly reported they *agree* or *definitely agree* they would consider purchasing a NIBS device to use at home if a trained professional was assisting through a video meeting. These responses speak to the potential for future research and clinical implementation for the use of tDCS, a portable, lightweight, and inexpensive methodology (Sauvaget et al., 2019), particularly home-based, remotely supervised tDCS (RS-tDCS) which delivers the same treatment one would receive in person except through supervision provided remotely with a device provided to the client that is programmed to administer a predetermined "dose" of tDCS when an assigned code is entered. RS-tDCS has shown evidence for use with a variety of conditions, including major depressive disorder (Cappon et al., 2022), aphasia (Richardson et al., 2023), and cognitive decline (Gough et al., 2020). There are potential challenges and limitations involved with home-based RS-tDCS administration, such as possible risks related to the loss of confidentiality, ensuring safety and client tolerability, client training and technical difficulties, and concerns that home administration may increase the burden on caregivers (Cucca et al., 2019; Pilloni et al., 2022). Despite these potential challenges, RS-tDCS remains an attractive future option that may allow autistic adults to receive treatment services in any location they choose, which suggests alignment with autistic prioritized treatment that supports lower anxiety and distress through fewer changes to routines and lowered environmental sensory demands, areas that often provide challenges for autistic individuals (Boulter et al., 2014).

Adult autistic respondents also reported they *agree* that NIBS is appealing as a possible alternative to other therapies, such as pharmaceuticals. This perspective may be accounted for by reports that 30–50% of autistic individuals are prescribed at least one psychotropic medication and 30% are prescribed three or more, despite the frequency of experiencing adverse side effects (Feroe et al., 2021).

Autistic adult respondents reported they *definitely agree* that NIBS should be used to address negative symptoms that reduce QoL, not trying to use NIBS to become more neurotypical. To this point, a notable feature of NIBS is its ability to provide highly individualized interventions by pairing evidence-based social interventions with NIBS based on the functional and structural anatomy and/or connectivity of each person to reach specifically targeted networks (Jog et al., 2019). This approach suggests partnerships for autistic prioritized outcomes that respect individual neurotypes, which is in alignment with the responses received from the majority of autistic adults who *agree* or *definitely agree* that they would like to play a role in developing their own treatment goals.

A limitation of this study is the small sample size of autistic adults in Study 2. There is a need for future research that gathers the input of a larger number of autistic adults on the topic of NIBS use. To this end, our research team has implemented a poststudy survey on NIBS use with all current and future autistic adults who are participating in our studies that utilize NIBS. Another limitation of this study is the possibility of selection bias related to the autistic adults who participated in Study 2. Given that these participants were a convenience sample available to the authors from previously completed studies, biases may be present based on prior experience with the study team and NIBS, although the prior experience with NIBS was key to why these participants were recruited. Again, this suggests the need for future studies with larger sample sizes to reduce the chance of selection bias and sampling error.

The findings of these two studies inform the future clinical implementation of NIBS in SLP practice for use in improving social communication and QoL for people with social communication challenges, including autistic adults.

Author Declarations

We have no known conflicts of interest to disclose. This work was completed without funding. The original research study that provided contact with the autistic adult respondents for this work was completed with support from the Mind Research Network, 1101 Yale Blvd. NE, Albuquerque, New Mexico 87106, USA.

References

Aishworiya, R., Valica, T., Hagerman, R., & Restrepo, B. (2022). An update on psychopharmacological treatment of autism spectrum disorder. *Neurotherapeutics, 19*(1), 248–262. https://doi.org/10.1007/s13311-022-01183-1

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). https://doi.org/10.1176/appi.books.9780890425596

American Speech-Language-Hearing Association. (2024a). *Social communication disorder*. https://www.asha.org/Practice-Portal/Clinical-Topics/Social-Communication-Disorder/

American Speech-Language-Hearing Association. (2024b). *The EBP process*. ASHA. https://www.asha.org/Research/EBP/Evidence-Based-Practice-Process/

Antal, A., Luber, B., Brem, A. K., Bikson, M., Brunoni, A. R., Cohen Kadosh, R., Dubljević, V., Fecteau, S., Ferreri, F., Flöel, A., Hallett, M., Hamilton, R. H., Herrmann, C. S., Lavidor, M., Loo, C., Lustenberger, C., Machado, S., Miniussi, C., Moliadze, V., … Paulus, W. (2022). Non-invasive brain stimulation and neuroenhancement. *Clinical Neurophysiology Practice, 7*, 146–165. https://doi.org/10.1016/j.cnp.2022.05.002

Ayres, M., Parr, J. R., Rodgers, J., Mason, D., Avery, L., & Flynn, D. (2018). A systematic review of quality of life of adults on the autism spectrum. *Autism, 22*(7), 774–783. https://doi.org/10.1177/1362361317714988

Baron-Cohen, S. (2009). Autism: The empathizing-systemizing (E-S) theory. *Annals of the New York Academy of Sciences, 1156*(1), 68–80. https://doi.org/10.1111/j.1749-6632.2009.04467.x

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism spectrum quotient: Evidence from Asperger syndrome/high functioning autism, males and females, scientists and mathematicians. *Journal of Autism and Developmental Disorders, 31*, 5–17. https://doi.org/10.1023/A:1005653411471

Bikson, M., Grossman, P., Thomas, C., Zannou, A. L., Jiang, J., Adnan, T., Mourdoukoutas, A. P., Kronberg, G., Truong, D., Boggio, P., Brunoni, A. R., Charvet, L., Fregni, F., Fritsch, B., Gillick, B., Hamilton, R. H., Hampstead, B. M., Jankord, R., Kirton, A., … Woods, A. J. (2016). Safety of transcranial direct current stimulation: Evidence based update 2016. *Brain Stimulation, 9*(5), 641–661. https://doi.org/10.1016/j.brs.2016.06.004

Boulter, C., Freeston, M., South, M., & Rodgers, J. (2014). Intolerance of uncertainty as a framework for understanding anxiety in children and adolescents with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 44*, 1391–1402. https://doi.org/10.1007/s10803-013-2001-x

Camm-Crosbie, L., Bradley, L., Shaw, R., Baron-Cohen, S., & Cassidy, S. (2019). 'People like me don't get support': Autistic adults' experiences of support and treatment for mental health difficulties, self-injury and suicidality. *Autism, 23*(6), 1431–1441. https://doi.org/10.1177/1362361318816053

Cappon, D., den Boer, T., Jordan, C., Yu, W., Lo, A., LaGanke, N., Biagi, M. C., Skorupinski, P., Ruffini, G., Morales, O., Metzger, E., Manor, B., & Pascual-Leone, A. (2022). Safety and feasibility of tele-supervised home-based transcranial direct current stimulation for major depressive disorder. *Frontiers in Aging Neuroscience, 13*, Article 765370. https://doi.org /10.3389/fnagi.2021.765370

Chan, M. M. Y., Choi, C. X. T., Tsoi, T. C. W., Shea, C. K. S., Yiu, K. W. K., & Han, Y. M. Y. (2023). Effects of multisession cathodal transcranial direct current stimulation with cognitive training on sociocognitive functioning and brain dynamics in autism: A double-blind, sham-controlled, randomized EEG study. *Brain Stimulation, 16*(6), 1604–1616. https://doi.org/10.1016/j.brs.2023.10.012

Connolly, K. R., Helmer, A., Cristancho, M. A., Cristancho, P., & O'Reardon, J. P. (2012). Effectiveness of transcranial magnetic stimulation in clinical practice post-FDA approval in the United States: Results observed with the first 100 consecutive cases of depression at an academic medical center. *Journal of Clinical Psychiatry, 73*(4), e567–e573. https://doi.org/10.4088/JCP.11m07413

Cucca, A., Sharma, K., Agarwal, S., Feigin, A. S., & Biagioni, M. C. (2019). Tele-monitored tDCS rehabilitation: Feasibility, challenges and future perspectives in Parkinson's disease. *Journal of NeuroEngineering and Rehabilitation, 16*(1), Article 20. https://doi.org/10.1186/s12984-019-0481-4

Esse Wilson, J., Trumbo, M. C., & Tesche, C. D. (2021). Transcranial direct current stimulation (tDCS) improves empathy and recognition of facial emotions conveying threat in adults with autism spectrum disorder (ASD): A randomized controlled pilot study. *NeuroRegulation, 8*(2), 87–95. https://doi.org/10.15540/NR.8.2.87

Esse Wilson, J., Trumbo, M. C., Wilson, J. K., & Tesche, C. D. (2018). Transcranial direct current stimulation (tDCS) over right temporoparietal junction (rTPJ) for social cognition and social skills in adults with autism spectrum disorder (ASD). *Journal of Neural Transmission, 125*(12), 1857–1866. https://doi.org/10.1007/s00702-018-1938-5

Esse Wilson, J., Quinn, D. K., Wilson, J. K., Garcia, C. M., & Tesche, C. D. (2018). Transcranial direct current stimulation to the right temporoparietal junction for social functioning in autism spectrum disorder. *The Journal of ECT, 34*(1), e10–e13. https://doi.org/10.1097/YCT.0000000000000445

Feroe, A. G., Uppal, N., Gutiérrez-Sacristán, A., Mousavi, S., Greenspun, P., Surati, R., Kohane, I. S., & Avillach, P. (2021). Medication use in the management of comorbidities among individuals with autism spectrum disorder from a large nationwide insurance database. *JAMA Pediatrics, 175*(9), 957–965. https://doi.org/10.1001/jamapediatrics.2021.1329

Filmer, H. L., Dux, P. E., & Mattingley, J. B. (2014). Applications of transcranial direct current stimulation for understanding brain function. *Trends in Neurosciences, 37*(12), 742–753. https://doi.org/10.1016/j.tins.2014.08.003

Gardner, W., Mulvey, E. P., & Shaw, E. C. (1995). Regression analyses of counts and rates: Poisson, overdispersed Poisson, and negative binomial models. *Psychological Bulletin, 118*(3), 392–404. https://doi.org/10.1037/0033-2909.118.3.392

Gough, N., Brkan, L., Subramaniam, P., Chiuccariello, L., De Petrilloid, A., Mulsant, B. H., Bowie, C. R., & Rajjiid, T. K. (2020). Feasibility of remotely supervised transcranial direct current stimulation and cognitive remediation: A systematic review. *PLoS ONE, 15*(2), Article e0223029. https://doi.org/10.1371/journal.pone.0223029

Hadoush, H., Nazzal, M., Almasri, N. A., Khalil, H., & Alafeef, M. (2020). Therapeutic effects of bilateral anodal transcranial direct current stimulation on prefrontal and motor cortical areas in children with autism spectrum disorders: A pilot study. *Autism Research, 13*(5), 828–836. https://doi.org/10.1002/aur.2290

Han, Y. M. Y., Chan, M. M. Y., Shea, C. K. S., Mo, F. Y. M., Yiu, K. W. K., Chung, R. C. K., Cheung, M. C., & Chan, A. S. (2023). Effects of prefrontal transcranial direct current stimulation on social functioning in autism spectrum disorder: A randomized clinical trial. *Autism, 27*(8), 2465–2482. https://doi.org/10.1177/13623613231169547

Happe, F., & Vital, P. (2009). What aspects of autism predispose to talent? *Philosophical Transactions of the Royal Society, 364*, 1369–1375. https://doi.org/10.1098/rstb.2008.0332

Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). Research electronic data capture (REDCap)—A metadata-driven methodology and workflow process for providing translational research informatics support. *Journal of Biomedical Informatics, 42*(2), 377–381. https://doi.org/10.1016/j.jbi.2008.08.010

Jog, M. V., Wang, D. J. J., & Narr, K. L. (2019). A review of transcranial direct current stimulation (tDCS) for the individualized treatment of depressive symptoms. *Personalized Medicine in Psychiatry, 17*, 17–22. https://doi.org/10.1016/j.pmip.2019.03.001

Keator, L. M., Basilakos, A., Rorden, C., Elm, J., Bonilha, L., & Fridriksson, J. (2020). Clinical implementation of transcranial direct current stimulation in aphasia: A survey of speech-language pathologists. *American Journal of Speech-Language Pathology, 29*(3), 1376–1388. https://doi.org/10.1044/2020_AJSLP-19-00037

Klinger, L. G., Cook, M. L., & Dudley, K. M. (2021). Predictors and moderators of treatment efficacy in children and adolescents with autism spectrum disorder. *Journal of Clinical Child & Adolescent Psychology, 50*(4), 517–524. https://doi.org/10.1080/15374416.2020.1833735

Leadbitter, K., Buckle, K. L., Ellis, C., & Dekker, M. (2021). Autistic self-advocacy and the neurodiversity movement: Implications for autism early intervention research and practice. *Frontiers in Psychology, 12*, Article 635690. https://doi.org/10.3389/fpsyg.2021.635690

Liu, A., Gong, C., Wang, B., Sun, J., & Jiang, Z. (2023). Non-invasive brain stimulation for patient with autism: A systematic review and meta-analysis. *Frontiers in Psychiatry, 14*, Article 1147327. https://doi.org/10.3389/fpsyt.2023.1147327

Lord, C., Rutter, M., DiLavore, P. C., Risi, S., Gotham, K., & Bishop, S. (2012). *Autism diagnostic observation schedule* (2nd ed.). Western Psychological Services.

Maenner, M. J., Warren, Z., Williams, A. R., Amoakohene, E., Bakian, A. V., Bilder, D. A., Durkin, M. S., Fitzgerald, R. T., Furnier, S. M., Hughes, M. M., Ladd-Acosta, C. M., McArthur, D., Pas, E. T., Salinas, A., Vehorn, A., Williams, S., Esler, A., Grzybowski, A., Hall-Lande, J., … Shaw, K. A. (2023). Prevalence and characteristics of autism spectrum disorder among children aged 8 years - Autism and developmental disabilities monitoring network, 11 sites, United States, 2020. *MMWR Surveillance Summaries, 72*(2), 1–14. https://doi.org/10.15585/mmwr.ss7202a1

Martin, A. K., Huang, J., Hunold, A., & Meinzer, M. (2019). Dissociable roles within the social brain for self-other processing: A HD-tDCS study. *Cerebral Cortex, 29*(8), 3642–3654. https://doi.org/10.1093/cercor/bhy238

Mattioli, F., Maglianella, V., D'Antonio, S., Trimarco, E., & Caligiore, D. (2024). Non-invasive brain stimulation for patients and healthy subjects: Current challenges and future perspectives. *Journal of the Neurological Sciences, 456*, Article 122825. https://doi.org/10.1016/j.jns.2023.122825

Mondino, M., Bennabi, D., Poulet, E., Galvao, F., Brunelin, J., & Haffen, E. (2014). Can transcranial direct current stimulation (tDCS) alleviate symptoms and improve cognition in psychiatric disorders? The *World Journal of Biological Psychiatry, 15*(4), 261–275. https://doi.org/10.3109/15622975.2013.876514

Palm, U., Schiller, C., Fintescu, Z., Obermeier, M., Keeser, D., Reisinger, E., Pogarell, O., Nitsche, M. A., Möller, H.-J., & Padberg, F. (2012). Transcranial direct current stimulation in treatment resistant depression: A randomized double-blind, placebo-controlled study. *Brain Stimulation, 5*(3), 242–251. https://doi.org/10.1016/j.brs.2011.08.005

Pilloni, G., Vogel-Eyny, A., Lustberg, M., Best, P., Malik, M., Walton-Masters, L., George, A., Mirza, I., Zhovtis, L., Datta, A., Bikson, M., Krupp, L., & Charvet, L. (2022). Tolerability and feasibility of at-home remotely supervised transcranial direct current stimulation (RS-tDCS): Single-center evidence from 6,779 sessions. *Brain Stimulation, 15*(3), 707–716. https://doi.org/10.1016/j.brs.2022.04.014

Qiao, Y., Hu, Q., Xuan, R., Guo, Q., Ge, Y., Chen, H., Zhu, C., Ji, G., Yu, F., Wang, K., & Zhang, L. (2020). High-definition transcranial direct current stimulation facilitates emotional face processing in individuals with high autistic traits: A sham-controlled study. *Neuroscience Letters, 738*, Article 125396. https://doi.org/10.1016/j.neulet.2020.135396

Ratner, N. B. (2006). Evidence-based practice: An examination of its ramifications for the practice of speech-language pathology. *Language, Speech, and Hearing Services in Schools, 37*(4), 257–267. https://doi.org/10.1044/0161-1461(2006/029)

Richardson, J. D., Galletta, E. E., Charvet, L., & Shaw, M. (2023). Feasibility of remotely supervised transcranial direct current stimulation (RS-tDCS) for people with stroke-induced and progressive aphasia. *Aphasiology, 37*(7), 1039–1063. https://doi.org/10.1080/02687038.2022.2076279

Rødgaard, E.-M., Jensen, K., Miskowiak, K. W., & Mottron, L. (2022). Representativeness of autistic samples in studies recruiting through social media. *Autism Research, 15*(8), 1447–1456. https://doi.org/10.1002/aur.2777

Romei, V., Borgatti, R., & Urgesi, C. (2019). Non-invasive brain stimulation for the rehabilitation of children and adolescents with neurodevelopmental disorders: A systematic review. *Frontiers in Psychology, 10*, Article 135. https://doi.org/10.3389/fpsyg.2019.00135

Roux, A. M., Rast, J. E., Rava, J. A., Anderson, K. A., & Shattuck, P. T. (2015). *National autism indicators report: Transition into young adulthood*. Life Course Outcomes Research Program, A. J. Drexel Autism Institute, Drexel University. https://drexel.edu/autismoutcomes/publications-and-reports/publications/National-Autism-Indicators-Report-Transition-to-Adulthood/

Sauvaget, A., Tostivint, A., Etcheverrigaray, F., Pichot, A., Dert, C., Schirr-Bonnais, S., Clouet, J., Sellal, O., Mauduit, N., Leux, C., Cabelguen, C., Bulteau, S., & Riche, V.-P. (2019). Hospital production cost of transcranial direct current stimulation (tDCS) in the treatment of depression. *Neurophysiologie Clinique, 49*(1), 11–18. https://doi.org/10.1016/j.neucli.2018.11.001

Schiltz, H., McVey, A. J., Dolan Wozniak, B., Haendel, A. D., Stanley, R., Arias, A., Gordon, N., & Van Hecke, A. V. (2021). The role of loneliness as a mediator between autism features and mental health among autistic young adults. *Autism, 25*(2), 545–555. https://doi.org/10.1177/1362361320967789

Vaismoradi, M., Jones, J., Turunen, H., & Snelgrove, S. (2016). Theme development in qualitative content analysis and thematic analysis. *Journal of Nursing Education and Practice, 6*(5), 100–110. https://doi.org/10.5430/jnep.v6n5p100

Zheng, E. Z., Wong, N. M. L., Yang, A. S. Y., & Lee, T. M. C. (2024). Evaluating the effects of tDCS on depressive and anxiety symptoms from a transdiagnostic perspective: A systematic review and meta-analysis of randomized controlled trials. *Translational Psychiatry, 14*(1), Article 295. https://doi.org/10.1038/s41398-024-03003-w

Received: September 18, 2024
Accepted: October 30, 2024
Published: March 24, 2025

NeuroRegulation

Audio-Visual Entrainment (AVE) Therapy in Reducing Symptoms of Pseudobulbar Affect (PBA): Two Case Studies

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Abstract

Introduction. Pseudobulbar affect (PBA) is characterized by involuntary episodes of laughter or crying, often associated with neurological disorders, significantly impacting the quality of life. This study investigates the effectiveness of audio-visual entrainment (AVE) therapy in reducing PBA symptoms. **Methods.** The study employed a one-group pretest–posttest experimental design with a sample of 472 individuals from Baghdad, Iraq. Two participants diagnosed with multiple sclerosis and amyotrophic lateral sclerosis underwent 40 AVE sessions over 2 months using the DAVID Delight Pro device. The Center for Neurologic Study-Lability Scale (CNS-LS) was used to measure PBA symptoms before and after the intervention, with a follow-up 3 months postintervention. **Results.** Both participants showed significant reductions in CNS-LS scores postintervention (male: 22 to 14; female: 25 to 12), indicating decreased frequency and intensity of emotional outbursts. The Wilcoxon signed-rank test revealed significant differences between pretest and posttest scores with a large effect size ($r \approx -0.95$). **Conclusion.** AVE therapy effectively reduces PBA symptoms, demonstrating lasting benefits at a 3-month follow-up. This study supports AVE as a promising nonpharmacological treatment for PBA, encouraging further research on its application to other neurological conditions.

Keywords: pseudobulbar affect (PBA); audio-visual entrainment (AVE); CNS-LS; neurological therapy; emotional dysregulation; nonpharmacological intervention

Citation: Al-Salihy, A. A.-R. S. (2025). Audio-visual entrainment (AVE) therapy in reducing symptoms of pseudobulbar affect (PBA): Two case studies. *NeuroRegulation, 12*(1), 40–50. https://doi.org/10.15540/nr.12.1.40

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Introduction

Pseudobulbar affect (PBA) is a neurological disorder characterized by sudden, involuntary, and often inappropriate episodes of uncontrollable laughter or crying, usually disproportionate to the individual's emotional state (Riera, 2024). It commonly manifests in individuals with conditions like multiple sclerosis (MS), traumatic brain injury (TBI), stroke, and amyotrophic lateral sclerosis (ALS; Jain, 2014; Schiffer & Pope, 2005). These episodes, which can be distressing and socially disruptive, significantly impair patients' quality of life by leading to embarrassment, social withdrawal, and difficulties in daily functioning (Cummings, 2017; Rosen, 2008). For some patients, these episodes can be partially controlled voluntarily, while for others, they are uncontrollable (Robinson-Smith & Grill, 2007).

The terminology surrounding PBA varies, with terms like emotional lability, pathological laughter and crying, and emotional incontinence often used interchangeably. Despite this variability, *pseudobulbar affect* remains the most widely accepted term in clinical practice and research (Ahmed & Simmons, 2013; Hicks et al., 2020).

Accurate diagnosis of PBA is challenging due to symptom overlap with other conditions such as depression, essential crying, dacrystic seizures, gelastic seizures, and rapid-cycling bipolar disorder, along with other mood disorders, which complicates effective management (Hicks et al., 2020; Miller et al., 2011; Work et al., 2011). Scientists attribute PBA to damage in brain regions responsible for regulating emotions and affect. Brain injuries or illnesses can trigger PBA symptoms, which are typically associated with conditions like stroke (28%), Alzheimer's disease/dementia (39%), MS (46%), Parkinson's disease (24%), and TBI (48%; King & Reiss, 2013; Schiffer & Pope, 2005). PBA is believed to result from brain lesions that disrupt the neural circuits regulating emotional expression (Work et al., 2011).

Current treatment approaches include medications like selective serotonin reuptake inhibitors (SSRIs) and the dextromethorphan-quinidine combination, although these offer only partial relief and come with potential side effects (Arciniegas et al., 2014; Schiffer & Pope, 2005). In this context, noninvasive interventions like audio-visual entrainment (AVE) therapy have gained attention. AVE uses rhythmic pulses of light and sound to modulate brainwave activity, promoting relaxation, cognitive enhancement, and mood stabilization (Gallina, 2022). It has shown efficacy in treating conditions such as anxiety, attention-deficit/hyperactivity disorder (ADHD), and chronic pain (Basu et al., 2024; Berg & Siever, 2009). Given its potential to influence neurophysiological processes without significant adverse effects, AVE may be a promising alternative for managing PBA symptoms (Aftanas et al., 2016; Bahrami, 2024).

This study aims to evaluate the effectiveness of AVE therapy in alleviating symptoms of PBA, marking the first investigation of its kind within the Arabic and Iraqi context. The operational definition of AVE in this research is based on its use through the DAVID Delight Pro device, which is widely recognized for its therapeutic applications across various neurological and psychological conditions (Siever, 2004). By addressing this gap in the literature, the study provides valuable insights and opens new avenues for exploring AVE’s potential in treating other neurological disorders. The significance of this research lies in several key aspects: It represents the first Arabic and Iraqi study to specifically address PBA and the first to explore the use of AVE technology for this condition at both the national and international levels. This research's findings can inspire further studies involving different populations and age groups affected by PBA. Additionally, this study lays the groundwork for investigating the broader applications of AVE technology in treating other disorders, thereby enriching scientific literature with cutting-edge research amidst ongoing technological advancements. The specific objectives of this research are to assess the prevalence and severity of PBA within a sample from the Iraqi community in Baghdad and to evaluate the effectiveness of AVE therapy in reducing PBA symptoms.

Research Scope. This study focuses on a sample of adults aged 18 and above residing in Baghdad Governorate during 2024. The sample includes individuals of both genders and various educational backgrounds. The scope is limited to Baghdad due to the challenges in finding sufficient participants diagnosed with PBA, leading to a restricted sample size.

Methods and Materials

This study utilized a one-group pretest–posttest experimental design to assess the effectiveness of AVE therapy in reducing PBA symptoms. This design measured participants’ symptoms before and after the intervention without including a control group. The target population for this research included adults aged 18 years and above residing exclusively in Baghdad Governorate during 2023 and 2024, covering both genders and all educational levels.

Due to the challenge of obtaining a sample of individuals diagnosed with PBA and the difficulty in locating such participants, social media platforms were used to distribute a survey incorporating the research tool, “the Center for Neurologic Study-Lability Scale (CNS-LS)” (Moore et al., 1997). The survey was shared voluntarily, allowing participation from anyone interested or experiencing psychological or neurological issues. The final sample comprised 472 participants with diverse educational backgrounds, including males and females. Table 1 outlines the details of the survey sample. It is important to note that formal informed consent was not obtained at this stage since the survey was conducted online. The participants had an average age of 28.56 years (SD = 9.23), ranging from 18 to 61 years.

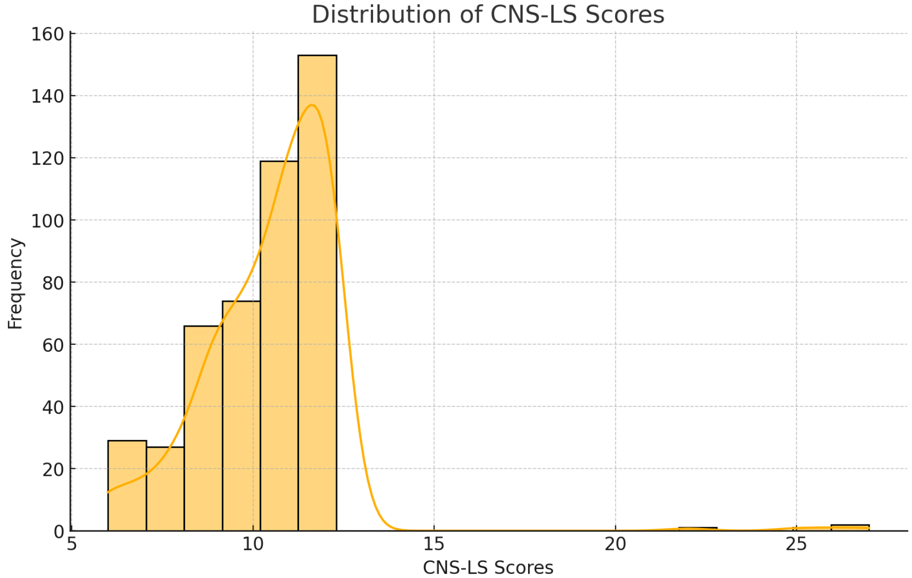
Table 1
Distribution of Survey Sample by Gender and Educational Level

Gender	Educational Level	Sample Size
	Elementary School	3
	High School	16
	Intermediate	7
	Institute (after Intermediate School)	3
Female	Institute (High School)	5
	College	248
	Master's Degree	38
	Doctorate	20
	Literate	12
Total for Females		**352**
	Elementary School	2
	High School	7
	Intermediate	1
	Institute (after Intermediate School)	1
Male	Institute (High School)	3
	College	63
	Master's Degree	19
	Doctorate	23
	Literate	1
Total for Males		**120**
Total Survey Sample		**472**

After administering the CNS-LS and analyzing the collected data, the results revealed key statistical information related to CNS-LS scores. The overall mean CNS-LS score for the survey sample was 10.56 (*SD* = 2.08), with males averaging a score of 10.26 (*SD* = 2.71) and females averaging 10.66 (*SD* = 1.80). The median CNS-LS score across all groups was 11.00, while the most frequently occurring score (*mode*) was 12.00. The *range* of CNS-LS scores spanned from a minimum of 6.00 to a maximum of 27.00 for the total sample. Notably, the sample comprised 472 participants, 120 males and 352 females. The confidence level for these findings was 95%, providing a solid basis for interpreting the data.

To further analyze the data distribution, a *Shapiro-Wilk* test was conducted to assess normality. The test produced a statistic of 0.727 with a *p*-value of 4.603×10^{-27}. Given that the *p*-value is well below the .05 threshold, we reject the null hypothesis that the data follow a normal distribution. These results confirm that the CNS-LS scores are not normally distributed (see Figure 1).

Figure 1. *Distribution of Raw Scores Obtained by Survey Sample Participants.*



Participants

The research population consisted of adults aged 18 to 61 years residing in Baghdad Governorate, representing both genders and various educational backgrounds. Given the rarity of PBA, the final sample included only two individuals who met the study's inclusion criteria: a 39-year-old male diagnosed with MS and a 39-year-old female diagnosed with amyotrophic ALS.

The study used a survey approach with 472 participants, screened using the CNS-LS. The survey was distributed online to identify individuals with high PBA scores. Out of the participants, only two were diagnosed with neurological conditions associated with PBA, reflecting the rarity of the condition in this population. Statistical analysis provided insights into the severity of symptoms, showing significant emotional lability in these identified cases.

Inclusion Criteria.

1. Diagnosis of a neurological disorder associated with PBA (e.g., MS, ALS).
2. Frequent episodes of emotional lability.
3. Willingness to participate for the entire duration of the study.

Exclusion Criteria

1. Absence of a neurological disorder associated with PBA.
2. Inability to complete the AVE therapy sessions.
3. Current use of medications that affect emotional lability.

This study was approved by the Scientific and Ethical Committee of the Iraqi Association for Psychotherapy (Approval Number: IAP-2023-04-05) on April 5, 2023. All participants provided informed consent prior to their inclusion in the study. The research was conducted following the ethical standards laid down in the 1964 Declaration of Helsinki (World Medical Association, 2013) and its later amendments. No experiments involving animals were conducted in this study.

Instruments

Pseudobulbar Affect (PBA) Scale. The CNS-LS is a self-assessment tool comprising seven items designed to measure the frequency of PBA symptoms. Although the scale has been translated into several languages (Chen et al., 2024), it has not previously been available for clinical or research use among Arabic-speaking populations. The CNS-LS allows respondents to assess their experiences with PBA symptoms, facilitating accurate and objective diagnosis by specialists. Originally developed and validated by Moore et al. (1997) in a population of patients with ALS and MS, the CNS-LS quantitatively evaluates aspects of PBA such as frequency, severity, emotional lability, degree of voluntary control, and appropriateness.

The scale includes four items related to laughter and three related to tears, each rated on a 5-point Likert scale (*never*, *rarely*, *occasionally*, *often*, *very often*), scoring from 1 to 5 per response. In patients with ALS, a score of 13 or higher suggests a likely diagnosis of PBA, while in those with MS, a score of

17 or higher indicates a high probability of PBA (Ahmed & Simmons, 2013; Moore et al., 1997).

Psychometric Properties of the PBA Scale.

a) ***Translation Validity.*** The research tool was translated from English to Arabic to ensure its suitability and validity in the Iraqi context. The back-translation method was employed to maintain translation accuracy (Butcher & Han, 1996). Two independent bilingual experts translated the items from English to Arabic, Professor Dr. Nabil Abdul Aziz Al-Badri (University of Tikrit) and the researcher. The translations were then consolidated into a single version and back-translated into English by Asst. Prof. Dr. Muzaffar Jawad Ahmed (Psychological Research Center, Ministry of Higher Education and Scientific Research) and the researcher. This back-translated version was compared with the original to ensure accuracy. Minor adjustments were made to align the psychological meanings with the Iraqi context. Finally, an Arabic language expert, Asst. Prof. Dr. Israa Al-Gharbawi (Psychological Research Center, Ministry of Higher Education and Scientific Research) reviewed the translation for linguistic accuracy.

b) ***Reliability*. The Cronbach's alpha coefficient** was calculated using data from 472 participants who completed the CNS-LS scale online as part of our search for individuals with PBA. The alpha value was approximately α = 0.73, indicating good internal consistency among the questionnaire items. This suggests that the CNS-LS questions reliably measure the intended concept. With Cronbach's alpha values ranging from 0 to 1, a value of 0.73 indicates an acceptable level of consistency, supporting the reliability of the scale results in this study (Cronbach, 1951).

Test-Retest Method*.* To assess reliability, the research tool was readministered online to a randomly selected sample of 50 individuals 2 weeks after their initial participation. This interval was chosen to ensure participant availability while maintaining consistency between tests. Pearson's correlation coefficient between the scores from both applications was calculated, resulting in a reliability coefficient of 0.81, indicating strong reliability (Weiten et al., 1991).

DAVID Delight Pro Device. The DAVID Delight Pro is a Canadian-made portable device offering nonpharmacological treatments for various conditions, including concussions, TBI, and cognitive disorders. It utilizes AVE and cranial electrotherapy stimulation (CES) technologies, which are noninvasive methods to enhance mental and physical performance. These technologies can be used individually or together to improve sleep, reduce cognitive decline, and treat conditions such as ADHD, seasonal affective disorder (SAD), depression, insomnia, and anxiety (Mind Alive Inc., 2024; see Figure 2).

Figure 2. *DAVID Delight Pro Device.*

The DAVID Delight Pro device consists of the Delight Pro unit, the patented multicolor glasses with a carrying case for the glasses, headphones, an A/C power adapter, an AUX stereo jack, a 9-volt battery, a handheld carrying case, a quick start guide, a user manual, and an instruction CD (see Figure 3).

Research has shown that AVE technology effectively guides the brain to different brainwave states, increases neurotransmitter production, and enhances cerebral blood flow. Additionally, CES technology effectively increases blood flow and stimulates neurotransmitters such as serotonin, endorphins, and norepinephrine (Aftanas et al., 2016; Siever, 2012).

Figure 3. *Components of the DAVID Delight Pro Device.*

The DAVID Delight Pro device offers five categories of therapeutic sessions: activation, meditation, brain booster, sleep, and mood enhancement, each with multiple options. It also features customizable sessions and incorporates CES technology with a 100 Hz frequency. The sessions are designed based on research to target various mental and physical functions, such as enhancing focus, improving sleep, and reducing stress (Mind Alive Inc., 2024).

Procedures

Given the difficulty in locating individuals diagnosed with PBA, social media platforms were used to distribute a survey incorporating the CNS-LS (Moore et al., 1997; Smith et al., 2004). The survey was completed by 472 participants via Google Forms between April 20, 2023, and January 27, 2024. Data analysis revealed a non-normal distribution, prompting the calculation of the 95th percentile (score = 12) to identify participants with high CNS-LS scores. Four participants exceeded this threshold, with two diagnosed with neurological conditions (MS and ALS) and scoring between 22 and 27. After structured interviews, two were excluded due to the absence of neurological conditions and PBA symptoms.

The two remaining individuals were confirmed to have neurological conditions, and the structured interviews further indicated that they exhibited symptoms consistent with emotional lability syndrome (see Table 2).

Table 2

Percentile Scores of Individuals Diagnosed With Neurological Diseases and Symptoms of Pseudobulbar Affect (PBA)

Gender	Age (Years)	Educational Level	Occupation	Suffering from MS, ALS, Alzheimer's Disease, or Parkinson's Disease	CNS-LS Score	Percentile
Male	39	Postgraduate	Employee	Yes	22	25.0
Female	39	College	Employee	Yes	25	50.0

After confirming the PBA diagnosis and obtaining participants' agreement, informed consent was secured for AVE therapy sessions. The process included:

1. **Pretest Assessment:** Participants completed a paper version of the CNS-LS to establish baseline emotional lability scores.
2. **AVE Therapy Intervention:** Over 2 months, participants underwent 40 AVE sessions using the DAVID Delight Pro device (20–30 min per session, five times weekly), primarily using the "brain boosting" mode.
3. **Posttest Assessment:** Participants retook the CNS-LS to assess symptom changes.
4. **Follow-Up Assessment:** 3 months postintervention, the CNS-LS was administered again, with regular check-ins for monitoring.

Data were collected at three points: pretest, posttest, and follow-up, utilizing interviews, observations, self-reports, and third-party feedback. The therapeutic program was then initiated accordingly.

Program Planning and Objectives

The program planning process involved defining the research objectives, outlining the scientific content, and clarifying the procedures, strategies, and approaches for applying AVE technology. The sessions were carefully structured by specifying their duration, type, and frequency. These sessions were conducted at the Iraqi Association for Psychotherapy in Baghdad from February 10, 2024, to April 11, 2024, with the primary goal of alleviating the symptoms of PBA in the participants.

Instructions for Implementing the Therapeutic Program

The program began with participant training, during which they were instructed on properly using the AVE device. This included the correct positioning of the glasses and headphones, along with a thorough explanation of the technology and details of each session. A presession protocol instruction guide was provided to support the participants' engagement. Additionally, two AVE devices were prepared for home use, with daily follow-ups to ensure adherence to the treatment schedule.

Participants were also advised to maintain healthy sleep and nutrition throughout the program. This included recommendations to sleep well and consume breakfast before the sessions while avoiding unhealthy foods that could potentially interfere with their overall well-being during the treatment. Biological factors, such as metabolism, were closely monitored, with reminders for participants to use the restroom before starting a session to prevent interruptions.

As part of the program guidelines, participants were instructed to avoid taking any medications, if possible, to ensure that external factors did not influence the effects of the AVE therapy. A quiet, distraction-free environment was recommended for the sessions to maximize the therapeutic effects. Each participant attended five weekly sessions, lasting between 20 and 30 min, over 2 months, completing 40 sessions. Upon completion of the program, the Emotional Lability scale was administered to assess the effectiveness of the therapy.

Session Content. Each session with the DAVID Delight Pro device is designed to modulate brainwave frequencies and improve cognitive function. Based on established literature and previous research using this technology, the "brain-boosting" session was identified as most suitable for achieving the study's goals. This session is recognized for enhancing focus, cognitive performance, and mental clarity. After the completion of 40 sessions, the devices were returned, and the posttest assessment using the Emotional Lability scale was administered to evaluate changes in participants' symptoms.

Data Analysis. Due to the small sample size and non-normal distribution of scores, nonparametric statistical methods were employed. The Wilcoxon signed-rank test was used to compare pretest and posttest CNS-LS scores, while effect sizes were calculated to assess the magnitude of observed changes.

Detailed Case Studies.

Case Study 1: Male, Age 39, Postgraduate Employee. This case involves a 39-year-old male diagnosed with MS 10 years ago. He frequently experienced episodes of emotional lability, characterized by uncontrollable laughter and crying, though he had no other significant comorbidities. His baseline characteristics included a CNS-LS pretest score of 22. He worked as an office employee, had a postgraduate degree, and lived in Baghdad with his wife and two children.

Before the intervention, the participant reported experiencing significant distress due to frequent emotional outbursts, which negatively impacted both his personal and professional life. To address this, he underwent a therapeutic intervention consisting of 40 AVE sessions conducted over 2 months, utilizing the brain boosting protocol.

Following the intervention, the participant's CNS-LS posttest score decreased to 14, indicating a marked improvement. Self-report questionnaires and interviews measured improvements in mood stability and overall mental well-being. Furthermore, feedback from family members and colleagues gathered through structured interviews revealed noticeable positive changes in his emotional regulation, demonstrating the effectiveness of AVE therapy.

Case Study 2: Female, Age 39, College Employee. This case centers around a 39-year-old female diagnosed with amyotrophic ALS 5 years ago. She frequently experienced uncontrollable crying episodes without any appropriate emotional triggers. Aside from her ALS diagnosis, she had no additional neurological or psychiatric conditions. At baseline, her CNS-LS pretest score was 25. She worked as an office employee, held a college degree, and lived in Baghdad as a single individual.

Before the intervention, the participant experienced significant distress due to unpredictable crying episodes, which severely impacted her social interactions and work performance. To address these symptoms, she underwent 40 AVE therapy sessions over 2 months, following the brain-boosting protocol.

Postintervention assessments showed a CNS-LS posttest score of 12, demonstrating a significant reduction in the frequency and severity of her crying episodes. Emotional stability and a noticeable decrease in anxiety, particularly in social settings, were reported through self-assessments and interviews. Additionally, structured interviews with her colleagues revealed positive feedback regarding her improved emotional control and professionalism, further validating the benefits of AVE therapy in managing her symptoms.

Follow-Up and Participant Retention. To assess the long-term effects of AVE therapy, follow-up evaluations were conducted 3 months postintervention using the CNS-LS, ensuring consistency with initial assessment methods. Participant retention was supported through regular contact via scheduled phone and email check-ins, reminding participants of upcoming assessments and addressing any concerns. The same assessment tools and procedures were applied consistently. Additionally, small incentives were provided to encourage continued participation and minimize dropout rates.

Statistical Methods. Data collected via Google Forms were exported as a Microsoft Excel file and then transferred to SPSS version 26.0 for analysis. The data were carefully reviewed for errors and omissions before proceeding with nonparametric statistical analysis. Microsoft Excel and SPSS were used to analyze the data and achieve the study's objectives.

Results

Various data collection methods were employed throughout the study to understand the participants' experiences comprehensively. Semistructured interviews were conducted before and after the intervention, focusing on emotional lability, the impact on daily life, and the participants' perceptions of AVE therapy. In addition to the interviews, participants were observed during the sessions to monitor their engagement and emotional responses. Any notable behavioral changes were carefully recorded.

Self-reported measures were also an integral part of the assessment process. CNS-LS scores were collected prior to the intervention and again after its completion, along with daily logs tracking emotional outbursts and mood fluctuations. External feedback from family members and colleagues was gathered as well in order to validate the participants' self-reported improvements and to identify any potential discrepancies between their perceptions and those of third parties.

The initial CNS-LS scores for the participants were 22 for the male and 25 for the female. After completing 40 AVE sessions, both participants exhibited significant improvements in their posttest scores, with the male scoring 14 and the female scoring 12 (see Table 3).

Table 3
Pretest and Posttest CNS-LS Scores for Sample Individuals

Gender	Pretest CNS-LS Score	Posttest CNS-LS Score
Male	22	14
Female	25	12

Follow-Up Results

At the 3-month follow-up, participants were reassessed using the CNS-LS. The results indicated that the improvements observed immediately postintervention were largely sustained, with participants maintaining lower CNS-LS scores than at baseline. These findings suggest that AVE therapy has a lasting effect on reducing symptoms of PBA.

Discussion

The 3-month follow-up results support the long-term efficacy of AVE therapy in reducing PBA symptoms. The sustained improvements in CNS-LS scores indicate that the benefits of AVE therapy extend beyond the immediate treatment period, highlighting its potential as a durable intervention for PBA. These results suggest that AVE therapy could provide a lasting solution for managing PBA symptoms, particularly important for improving the quality of life in individuals with neurological conditions.

The persistence of these benefits over 3 months suggests that AVE therapy may induce long-term neurophysiological changes. This durability is crucial because it implies that the therapy does not merely provide temporary relief but could potentially alter underlying neural mechanisms associated with PBA. Further follow-up at longer intervals (e.g., 6 months, 1 year) is recommended to confirm these findings and explore the persistence of treatment effects over time. Longitudinal studies will be essential to understand how AVE therapy maintains its effects and whether periodic booster sessions are necessary to sustain these benefits.

When comparing the results of the current study with those of other studies, significant agreement is found. Thomas and Siever (1989) showed significant improvements in motor activity and vascular motor activity using AVE technology, supporting its effectiveness in enhancing physiological responses. Joyce and Siever (2000) demonstrated that AVE technology effectively reduced behavioral disorders in a school environment, enhancing learning. Berg and Siever (2004) found a significant reduction in depressive symptoms in elderly individuals using AVE technology, indicating its benefit as a nonpharmacological treatment. Siever (2008) reported improvements in attention and cognitive functions, supporting its use in educational settings. Siever and Collura (2017) highlighted the positive impact of AVE technology on brainwave patterns and improvements in anxiety, ADHD, and cognitive decline. These studies collectively reinforce the therapeutic potential of AVE technology across various domains.

Regarding PBA studies, the PRISM Study Team (Brooks et al., 2013) confirmed the prevalence of PBA symptoms across multiple neurological conditions, providing valuable epidemiological data. This extensive data set underscores the widespread impact of PBA and the necessity for effective interventions. The Cleveland Clinic (2025) focused on the effectiveness of the dextromethorphan/quinidine (DM/Q) combination in reducing PBA episodes in patients with amyotrophic ALS and MS. Their findings align with the current study, demonstrating that targeted interventions can significantly mitigate PBA symptoms. The Mayo Clinic Staff (2018) study demonstrated that Nuedexta, a combination of DM/Q, reduced the frequency and severity of PBA episodes, making it an effective treatment option. This further supports the role of pharmacological treatments in managing PBA symptoms, albeit with potential side effects. Finally, Young and Nguyen (2020) highlighted the effectiveness of DM/Q treatment in a complex case of PBA, supporting its use in severe neurological cases. This case study approach provides a detailed understanding of how AVE technology and pharmacological treatments can be integrated for comprehensive PBA management.

The evidence from these studies collectively supports the effectiveness of AVE technology as a treatment for PBA symptoms, confirming our study's results and enhancing confidence in using AVE technology as an effective therapeutic method. The alignment of findings across different studies and conditions emphasizes the robustness of AVE technology as a versatile and potent intervention.

Limitations

Some limitations in this study should be considered. The small sample size is a notable constraint, reflecting PBA's inherent rarity, making finding more cases difficult. Given the limited availability of individuals with PBA, recruiting a control group was deemed impractical and scientifically irrelevant for this research, as including individuals without neurological conditions would not provide meaningful comparisons.

The recruitment process was conducted through an online public form, where participants voluntarily completed the survey. Since participation was anonymous and voluntary, informed consent was not required at this initial screening stage. However, formal consent was obtained from the final participants before the intervention phase began.

Potential confounding factors, such as variations in daily routines, dietary habits, or concurrent therapies, could have influenced the outcomes. Controlling these variables in a real-world setting is nearly impossible, but future studies might explore more controlled environments or detailed participant monitoring to address these issues.

Despite these limitations, the study provides valuable preliminary insights into the potential efficacy of AVE therapy for managing PBA symptoms and sets a foundation for larger, more controlled investigations.

Recommendations

Based on the findings of this research, several recommendations are proposed to enhance the use of AVE technology and its integration into therapeutic practices. First, combining AVE technology with psychotherapy is highly recommended to avoid the adverse side effects often associated with pharmacological treatments. This combination could yield the most effective therapeutic results, offering a holistic approach to managing conditions like PBA.

Additionally, AVE technology should be applied to other neurological and psychological patient groups. Given AVE therapy's noninvasive and side-effect-free nature, many patients could benefit from this innovative approach, making it a valuable addition to existing treatment options.

Further efforts should focus on providing advanced laboratory devices that align with contemporary Neurotherapy techniques. These devices are essential for effectively treating a wide range of psychological, mental, and neurological disorders, enabling more precise and personalized interventions.

Finally, there is a pressing need to establish psychological and neurological laboratories equipped with AVE technology. Incorporating these laboratories into the curriculum for undergraduate and graduate students is crucial, as they play a significant role in developing modern psychotherapeutic and neurotherapeutic methods and techniques. This will enhance educational outcomes and advance clinical practice in these fields.

Suggestions

In light of the study's findings, several suggestions are proposed to advance the application of AVE technology and related research. It is recommended that similar studies be conducted with additional demographic variables to broaden the understanding of how different populations respond to AVE therapy. Expanding the scope to include more diverse demographic groups would provide deeper insights and strengthen the generalizability of the findings.

Similar studies nationwide by colleges and universities are also suggested to identify the primary issues affecting these populations. The results of such studies should be communicated to decision-makers, allowing them to implement appropriate measures to address the identified problems.

Furthermore, there is merit in utilizing international measurement tools that have been standardized for the Iraqi environment. By incorporating global benchmarks, researchers can enhance the comparability of findings across different settings while maintaining local relevance.

It is also worth exploring the application of AVE technology in treating other neurological disorders. Given its effectiveness in managing PBA symptoms, AVE may benefit other conditions.

Media awareness campaigns are highly recommended to encourage the widespread use of AVE technology. These campaigns would play a crucial role in informing the public about the advantages of utilizing safe, noninvasive technologies such as AVE to enhance mental functioning and alleviate the symptoms associated with neurological disorders.

Finally, encouraging further research on biofeedback and neurofeedback devices is essential. Opening the field to new studies that investigate the use of these devices in daily life and mental health, alongside psychotherapy, could lead to innovative approaches to treating various psychological and neurological conditions.

Author Acknowledgments

The author would like to thank the participants for their involvement in the study and the Iraqi Association for Psychotherapy for their support. Special thanks to my colleagues for their insightful discussions and feedback. Finally, heartfelt thanks to my family and friends for their unwavering support.

Author Disclosures

As the author of this review, I confirm that I have no financial interest in any company or its competitor that manufactures a product discussed in this review or editorial. I have no grant or other financial support to disclose for the submitted manuscript. I declare no conflicts of interest that must be acknowledged concerning the submitted manuscript. Raw data generated during the study are available from the corresponding author upon request.

References

Aftanas, L., Miroshnikova, P. V., Morozova, N. B., Yarosh, S. V., Gilinskaya, O. M., & Khazankin, G. R. (2016). *Audio-visual-tactile brainwave entrainment decreases night arterial blood pressure in patients with uncontrolled essential hypertension: Placebo controlled study* [Paper presentation]. SAN2016 Meeting, Corfu, Greece. https://doi.org/10.3389/conf.fnhum.2016.220.00063

Ahmed, A., & Simmons, Z. (2013). Pseudobulbar affect: Prevalence and management. *Therapeutics and Clinical Risk Management, 9*, 483–489. https://doi.org/10.2147/TCRM.S53906

Arciniegas, D. B., Lauterbach, E. C., Ginsberg, D. L., Anderson, K. E., Chow, T. W., Flashman, L. A., Hurley, R. A., Kaufer, D. I., McAllister, T. W., Reeve, A., Schiffer, R. B., & Silver, J. M. (2014). The differential diagnosis of pseudobulbar affect (PBA): Distinguishing PBA among disorders of mood and affect. *CNS Spectrums, 10*(S5), 1–16. https://doi.org/10.1017/S1092852900026602

Bahrami, S. (2024). Utilizing music therapy for enhanced recovery from neurologic disease complications. *SVOA Neurology, 5*(1), 7–20. https://doi.org/10.58624/SVOANE.2024.05.0121

Basu, S., Phogat, R., Banerjee, B., & Parmananda, P. (2024). Visual entrainment improving working memory of children with and without ADHD/ASD: Preliminary observations. *Journal of Indian Association for Child and Adolescent Mental Health, 20*(3), 229–241. https://doi.org/10.1177/09731342241252533

Berg, K., & Siever, D. (2004). *The effect of audio-visual entrainment in depressed community-dwelling senior citizens who fall. In-house manuscript.* Mind Alive Inc.

Berg, K., & Siever, D. (2009). A controlled comparison of audio-visual entrainment for treating seasonal affective disorder. *Journal of Neurotherapy, 13*(3), 166–175. https://doi.org/10.1080/10874200903107314

Brooks, B. R., Crumpacker, D., Fellus, J., Kantor, D., & Kaye, R. E. (2013). PRISM: A novel research tool to assess the prevalence of pseudobulbar affect symptoms across neurological conditions. *PLoS ONE, 8*(8), Article e72232. https://doi.org/10.1371/journal.pone.0072232

Butcher, J. N., & Han, K. (1996). Methods of establishing cross-cultural equivalence. In J. N. Butcher (Ed.), *International adaptations of the MMPI-2: Research and clinical applications* (pp. 44–63). University of Minnesota Press.

Chen, L., Ye, S., Murphy, D., Wu, J., Zhang, H., Liu, H., Zou, B., Hou, G., Zhang, N., Yin, T., Smith, R. A., & Fan, D. (2024). Chinese translation and validation of the center for neurologic study lability scale. *Neurology and Therapy, 13*(3), 739–747. https://doi.org/10.1007/s40120-024-00605-w

Cleveland Clinic. (2025). *Pseudobulbar affect (PBA): Causes, symptoms & treatment*. Cleveland Clinic. Retrieved March 2, 2025. https://my.clevelandclinic.org/health/diseases/17928-pseudobulbar-affect-pba

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika, 16*(3), 297–334. https://doi.org/10.1007/BF02310555

Cummings, J. L. (2017). Pseudobulbar affect. In B. Tousi & J. Cummings (Eds.), *Neuro-Geriatrics* (pp. 389–393). Springer.

Gallina, J. (2022). *Alpha oscillations index the functionality and the plastic changes of the visual system* [Dissertation thesis], University of Bologna. https://doi.org/10.48676/unibo/amsdottorato/10265

Hicks, A. J., Clay, F. J., Ponsford, J. L., Perry, L. A., Jayaram, M., Batty, R., & Hopwood, M. (2020). Pharmacotherapy for the pseudobulbar affect in individuals who have sustained a traumatic brain injury: A systematic review. *Neuropsychology Review, 30*, 28–50. https://doi.org/10.1007/s11065-020-09427-7

Jain, S. (2014). Pseudobulbar affect: No laughing matter. *Current Psychiatry, 13*(4), 66–67.

Joyce, M., & Siever, D. (2000). Audio-visual entrainment program as a treatment for behavior disorders in a school setting. *Journal of Neurotherapy, 4*(2), 9–15. https://doi.org/10.1300/J184v04n02_04

King, R. R., & Reiss, J. P. (2013). The epidemiology and pathophysiology of pseudobulbar affect and its association with neurodegeneration. *Degenerative Neurological and Neuromuscular Disease, 3*, 23–31. https://doi.org/10.2147/DNND.S34160

Mayo Clinic Staff. (2018). *Diagnosis and treatment of pseudobulbar affect*. Mayo Clinic Staff. https://www.mayoclinic.org/diseases-conditions/pseudobulbar-affect/diagnosis-treatment/drc-20353741

Miller, A., Pratt, H., & Schiffer, R. B. (2011). Pseudobulbar affect: The spectrum of clinical presentations, etiologies and treatments. *Expert Review of Neurotherapeutics, 11*(7), 1077–1088. https://doi.org/10.1586/ern.11.68

Mind Alive Inc. (2024). *Now there is a pharmaceutical-free way to manage Concussion/Brain Injury/TBI.* Concussion & Brain Injury. https://mindalive.com/collections/concussion-and-brain-injury

Moore, S. R., Gresham, L. S., Bromberg, M. B., Kasarkis, E. J., & Smith, R. A. (1997). A self report measure of affective lability. *Journal of Neurology, Neurosurgery, & Psychiatry, 63*(1), 89–93. https://doi.org/10.1136/jnnp.63.1.89

Riera, A. R. P. (2024). *The role of facies in clinical diagnosis*: Cambridge Scholars Publishing.

Robinson-Smith, G., & Grill, J. D. (2007). Recognizing involuntary emotional expression disorder. *Journal of Neuroscience Nursing, 39*(4), 202–207. https://doi.org/10.1097/01376517-200708000-00003

Rosen, H. (2008). Dextromethorphan/quinidine sulfate (Zenvia) for pseudobulbar affect. *Drugs of Today (Barcelona, Spain: 1998), 44*(9), Article 661. https://doi.org/10.1358/dot.2008.44.9.1258664

Schiffer, R., & Pope, L. E. (2005). Review of pseudobulbar affect including a novel and potential therapy. *The Journal of Neuropsychiatry Clinical Neuroscience, 17*(4), 447–454. https://doi.org/10.1176/jnp.17.4.447

Siever, D. (2004). Audio-visual entrainment: The neurobiology of affective disorders and clinical implications of audio-visual entrainment. *Biofeedback Magazine, 32*(4), 1–15.

Siever, D. (2008). Applying audio-visual entrainment technology for attention and learning (Part 3). *Biofeedback Magazine, 31*(4), 1–15. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=480f1b101cd24fcbc30e92347e0012fd49e2a937

Siever, D. (2012). Audio-visual entrainment: A novel way of boosting grades and socialization while reducing stress in the typical college student. *Biofeedback, 40*(3), 115–124. https://doi.org/10.5298/1081-5937-40.3.02

Siever, D., & Collura, T. (2017). Audio–visual entrainment: Physiological mechanisms and clinical outcomes. In J. R. Evans & R. P. Turner (Eds.), *Rhythmic stimulation procedures in neuromodulation* (pp. 51–95). Academic Press.

Smith, R. A., Berg, J. E., Pope, L. E., Callahan, J. D., Wynn, D., & Thisted, R. A. (2004). Validation of the CNS emotional lability scale for pseudobulbar affect (pathological laughing and crying) in multiple sclerosis patients. *Multiple Sclerosis Journal, 10*(6), 679–685. https://doi.org/10.1191/1352458504ms1106oa

Thomas, N., & Siever, D. (1989). The effect of repetitive audio/visual stimulation on skeletomotor and vasomotor activity. In D. Waxman, D. Pederson, I. Wilkie, & P. Meller, (Eds.), *Hypnosis: 4th European Congress at Oxford* (pp. 238–245). Whurr Publishers.

Weiten, W., Lloyd, M. A., & Lashley, R. L. (1991). *Psychology applied to modern life adjustment in the 90s* (3rd ed.). Thomson Brooks/Cole Publishing Co.

Work, S. S., Colamonico, J. A., Bradley, W. G., & Kaye, R. E. (2011). Pseudobulbar affect: An under-recognized and under-treated neurological disorder. *Advances in Therapy, 28*(7), 586–601. https://doi.org/10.1007/s12325-011-0031-3

World Medical Association. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *JAMA, 310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Young, F. G., & Nguyen, D. (2020). Treatment of pseudobulbar affect (PBA) in a patient with a history of traumatic brain injury, partial brain resection, and brainstem stroke: A case report. *Journal of Medical Case Reports, 14*(1), Article 235. https://doi.org/10.1186/s13256-020-02525-3

Received: July 19, 2024
Accepted: December 01, 2024
Published: March 24, 2025

NeuroRegulation

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Effectiveness of Brain-Computer Interface (BCI)-Based Attention Training Game System for Symptom Reduction, Behavioral Enhancement, and Brain Function Modulation in Children With ADHD: A Systematic Review and Single-Arm Meta-Analysis

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Abstract

Introduction. Brain-computer interface (BCI)-based games have been developed as an adjunct to conventional ADHD therapy. This review aims to assess the effectiveness of these systems. **Methodology.** ADHD Rating Scale (ADHD-RS) and Integrated Visual and Auditory Continuous Performance Test (IVA-CPT) scores were analyzed, while other outcomes were assessed qualitatively. **Results.** Eleven studies with a total of 421 subjects were included, which utilized seven unique BCI-based games. There was a significant reduction in parent-reported (*MD* = 2.20; 95% CI: 0.91–3.49) and clinician-reported (*MD* = 1.60; 95% CI: 0.32–2.88) inattention (IA) scores in the intervention group versus control. There was a statistically significant reduction in parent-reported (*MD* = 3.70; 95% CI: 2.11–5.29) and clinician-reported (*MD* = 3.20; 95% CI: 1.82–4.58) IA scores and parent-reported hyperactive/impulsivity (HI) scores (*MD* = 3.88; 95% CI: 1.88–5.87) in a pre–post intervention analysis. IVA-CPT visual and auditory scores showed a statistically significant increase in the response control (*MD* = 12.85; 95% CI: 6.01–19.68) and attention (*MD* = 22.93; 95% CI: 15.44–30.43) quotients. Three studies reported a statistically significant reduction in Child Behavior Checklist (CBCL) scores. One study found a significant change in small-worldness over time (*P* = .045), indicating altered brain network structure after BCI-based attention training. **Conclusion.** BCI-based interventions show promise in controlling inattentive, hyperactive-impulsive, behavioral, and learning disability symptoms of ADHD, but further research is needed on a more holistic approach targeting both inattention and learning symptoms simultaneously.

Keywords: attention-deficit/hyperactivity disorder (ADHD); brain-computer interface (BCI); game; neurofeedback

Citation: Raza, M. Z., Omais, M., Arshad, M. E., Maqsood, M., & Nadeem, A. A. (2025). Effectiveness of brain-computer interface (BCI)-based attention training game system for symptom reduction, behavioral enhancement, and brain function modulation in children with ADHD: A systematic review and single-arm meta-analysis. *NeuroRegulation, 12*(1), 51–78. https://doi.org/10.15540/nr.12.1.51

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Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a chronic developmental disorder that begins in childhood and can persist into adulthood (Carlson et al., 1999). It is traditionally categorized into three types: the inattentive type, characterized by easy distraction and difficulties in sustaining attention; the hyperactive/impulsive type, marked by hyperactivity, excessive talking, fidgeting, and a lack of impulse control; and the combined type, which includes symptoms of both inattention and hyperactivity (Carlson et al., 1999). The inattentive type is the most prevalent, while the hyperactive/impulsive type is the least common (Ayano et al., 2020). Therapies for ADHD often focus on managing attentional symptoms, as these are central to the disorder's diagnostic criteria and significantly impact daily functioning. These symptoms include problems with task organization, frequent careless mistakes, and poor school performance. EEG analyses have revealed characteristic brain function disruptions in ADHD patients, such as decreased beta waves (associated with attention), decreased alpha waves (associated with relaxation), and increased theta waves (associated with inattention; Adamou et al., 2020). Furthermore, it is also associated with altered intrinsic brain network organization, including hyperconnectivity within the default mode network (DMN) involved in self-referential mental activity, the ventral attention network (VAN) responsible for orienting attention to salient stimuli, and between the VAN and the dorsal attention network (DAN), which helps in directing attention to task-relevant information (Castellanos & Proal, 2012; Konrad & Eickhoff, 2010; Sidlauskaite et al., 2016).

In typical brain networks, the architecture exhibits a balance of high local clustering of neurons and short path lengths, reflecting an optimal mix of local efficiency (specialized processing within clusters) and global efficiency (integrated processing across distant regions). This configuration is characteristic of a small-world network, which combines strong local connections for efficient segregated processing and long-range connections that enable effective communication across the entire brain. Such a balance supports both simple, localized tasks and complex, distributed cognitive functions. In contrast, brain networks in individuals with ADHD tend to shift toward a nonrandom configuration (Sporns, 2011). These networks are characterized by increased local clustering and longer path lengths, resulting in high local efficiency but reduced global efficiency. This disrupted balance limits the brain's ability to integrate information across distant regions, contributing to impairments in attention, executive function, and other distributed cognitive tasks (Watts & Strogatz, 1998).

Attention training can significantly improve the symptoms by enhancing an individual’s ability to focus, sustain attention, and regulate cognitive processes (Jensen et al., 2016). This training typically involves structured exercises and strategies designed to increase attentional control, such as practicing concentration on specific tasks and employing cognitive-behavioral techniques like social planning, self-monitoring, and behavioral activation (Jensen et al., 2016). Alternatively, neurofeedback (NF) therapy has emerged as an innovative method for attention training, which utilizes EEG data to help individuals self-regulate their brain activity (Arns et al., 2009; Enriquez-Geppert et al., 2019). The procedure involves placing electrodes on the scalp to monitor brain wave patterns and providing immediate feedback to participants through visual or auditory signals (Marzbani et al., 2016). Over time, participants train their brains to enhance desirable patterns, such as those associated with attention and executive function, and to reduce those associated with ADHD symptoms (Marzbani et al., 2016). A well-established NF framework involves leveraging adaptive neuroplasticity, which occurs through long-term potentiation (LTP) of neural synapses in brain regions associated with attention, executive function, and working memory, such as the dorsolateral prefrontal cortex, caudate nucleus, and hippocampus (Abarbanel, 1999; Trojan & Pokorný, 1999). Traditional treatments, including medications such as methylphenidate and atomoxetine, enhance LTP by increasing presynaptic levels of norepinephrine (NE; Piña et al., 2020; Rozas et al., 2015). NE acts on beta-adrenergic receptors to improve LTP, particularly in the hippocampus (Piña et al., 2020; Rozas et al., 2015). An alternative to medication, NF, is also proposed for ADHD treatment. Although NF does not directly increase neurotransmitter levels as medications do, it promotes LTP through long-term or repetitive stimulation (Abarbanel, 1999). NF enhances synaptic invaginations and increases the number of postsynaptic receptors (Trojan & Pokorný, 1999). The benefit derived from these approaches lies in the hippocampus's ability to induce LTP in cortical neurons, particularly in the prefrontal cortex (Abarbanel, 1999). This is significant because the hippocampus plays a crucial role in learning and memory, while the prefrontal cortex is essential for executive functions and attention. Consequently, NF training has the potential to enhance neuroplasticity in the prefrontal cortex, which may be particularly beneficial for reducing ADHD symptoms, especially those related to inattention (Abarbanel, 1999).

However, a key drawback of NF therapy lies in the classic correlation-versus-causation problem: NF systems rely on monitoring brain rhythms correlated with attention levels, but these correlations do not necessarily imply direct causation. For example, an increase in certain brain wave activity might be associated with improved attention, but it doesn’t confirm that the subject's attention directly caused the change in brain wave patterns (Lim et al., 2010). This ambiguity raises questions about the effectiveness observed with NF in previous studies.

To address this issue, a more innovative design has emerged (i.e., BCI-based gaming systems).

Brain-computer interface (BCI) engineering involves the acquisition, processing, and interpretation of neural signals to enable direct interaction between the brain and external systems. While both BCI and NF use similar electrode-based technology to capture brain signals, BCIs differ fundamentally in purpose and function. In traditional NF, brainwave patterns are merely displayed to the user, who learns to self-regulate brain activity over time; however, the user has no direct control over external systems. In contrast, BCIs enable individuals to actively control external devices or virtual elements by decoding neural signals into commands, creating an interactive feedback loop that goes beyond self-regulation (Mridha et al., 2021). For example, in stroke rehabilitation, BCIs help patients control robotic devices or simulate movement, which aids motor recovery (Sebastián-Romagosa et al., 2023). In epilepsy, BCIs monitor brain activity to predict and manage seizures (Gummadavelli et al., 2018), and in Parkinson's disease, they assist in rehabilitating motor functions (Bronte-Stewart et al., 2020). For mental health, BCIs provide novel interventions by modulating brain activity, such as through BCI music therapy for depression and anxiety (Sun, 2022).

Several studies have indicated that gaming can be helpful in ADHD patients due to its dynamic, engaging environments that stimulate processes such as attention and executive function, which are often impaired in ADHD (Peñuelas-Calvo et al., 2022). Games with adaptive difficulty levels and real-time feedback can enhance neural plasticity by reinforcing attention-related brain networks and improving cognitive control through repetitive, task-oriented practice (Kovacevic et al., 2015). BCI-based gaming is effective because it adapts gameplay based on the users' brain activity, helping to keep them engaged and focused on the in-game tasks. These systems operate on the principle of active and passive BCI technologies. Active BCIs require users to consciously focus their attention or perform specific mental tasks to influence the game or application, while passive BCIs monitor brain activity to detect subconscious changes in mental states, such as attention levels or relaxation, and adapt the game to subtly influence the user to alter these states. Studies have used both active and passive BCI techniques for attention training in children with ADHD (Zander et al., 2010). Both these systems offer distinct yet complementary benefits for ADHD management. While many individual trials have shown promising effects of this type of intervention as the primary treatment, there are few works that comprehensively compile and systematically compare their results, and none of them have focused on treatment outcomes (Cervantes et al., 2023). The objective of this review is to evaluate the impact of BCI-based games on ADHD symptoms, behavioral performance, and brain function, providing a comprehensive assessment of their efficacy in improving behavioral and learning outcomes in affected children.

Methods

This systematic review was written in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol was registered on the Open Science Framework (OSF) register (Raza et al., 2024).

Study Outcomes

There were two primary outcomes: (a) improvement in inattentive and hyperactive symptoms of ADHD and (b) improvement in behavior pattern of the child. Improvement in inattentive and hyperactive symptoms was represented by the change in the inattention (IA) and hyperactive-impulsivity (HI) scores measured with the ADHD Rating Scale (ADHD-RS), Integrated Visual and Auditory Continuous Performance Test (IVA-CPT), Clinical Global Impression-Severity (CGI-S) scale, and Children Global Assessment Scale (CGAS). Improvement in the behavior pattern was represented by the change in the scores measured with the Child Behavior Checklist (CBCL; Nøvik, 1999). Refer to Table 1 for details regarding these scales. There was one secondary outcome, brain function modulation, which was represented in this review by the changes in EEG patterns or brain network connectivity observed with functional MRI (fMRI) following the intervention.

Search Strategy

Four databases (PubMed, Cochrane CENTRAL, ScienceDirect, and IEEE Xplore) and two trial registers (ClinicalTrials.gov and WHO ICTRP) were searched without any date restrictions in July 2024. The search used both controlled vocabulary and text words for the terms "attention deficit hyperactivity disorder (ADHD)" and "brain-computer interface (BCI)". The specific search strategies for individual sources are given in Table 1A.

Table 1

List of All Assessments/Scales Used to Assess Outcomes of ADHD

Assessment/Scales	Abbreviation	Explanation
Diagnostic and Statistical Manual of Mental Disorders	DSM-IV (or V)	Prespecified diagnostic criteria for ADHD
ADHD Rating Scale	ADHD-RS	An 18-point questionnaire based on DSM-IV criteria for diagnosing and assessing ADHD severity. It has two subscales, inattention and hyperactive/impulsivity (DuPaul et al., 1998)
Inattention score	IA	Inattention score as measured by the ADHD-RS (DuPaul et al., 1998)
Hyperactive/impulsivity score	HI	Hyperactivity and impulsivity score as measured by the ADHD-RS (DuPaul et al., 1998)
Integrated Visual and Auditory Continuous Performance Test	IVA-CPT	A computerized visual and auditory attention test, wherein responses to objects on a screen requiring impulse control and avoiding errors of omission are scored on visual and auditory primary scales to derive scores (Tinius, 2003)
Clinical Global Impression-Severity	CGI-S	A scale assessing the severity of psychiatric symptoms, with higher scores indicating greater symptom severity (Berk et al., 2008)
Children Global Assessment Scale	CGAS	A scale that assesses the overall functioning of the child, with higher scores indicating better performance in various domains of life, such as academic performance and social relationships (Shaffer, 1983)
Child Behavior Checklist	CBCL	A scale for behavior pattern used in this study to measure improvement in symptoms by evaluating changes in scores. It encompasses two major categories of problems: externalizing and internalizing, as well as several minor categories including social, thought, and attention problems. Externalizing problems include behaviors such as lying, cheating, and aggression toward others, whereas internalizing problems involve issues like anxiety, social withdrawal, depression, and somatic complaints such as headaches and fatigue (Nøvik, 1999)

Eligibility Criteria

A study was deemed eligible if it met all of the following inclusion criteria: (a) children aged 12 years or younger diagnosed with ADHD, according to either DSM-IV or DSM-V criteria; (b) patients who received BCI-based attention training game system as the sole intervention; (c) studies must be randomized-controlled trials (RCTs), nonrandomized controlled trials (nRCTs), single-arm experimental trials, or prospective cohort studies; and (d) outcome measures include postinterventional changes in symptoms, behavior, learning disabilities, or brain functions. A study was deemed ineligible if it met at least one of the following exclusion criteria: (a) studies in which most of the participants are taking either stimulant medications, supplements, or both concomitantly or within 1 month prior to starting BCI-based therapy because these substances can significantly improve attention and cognitive control, making it difficult to isolate the true effect of the BCI intervention; (b) patients who have predominantly hyperactive/impulsive symptoms because BCI-based therapy primarily targets attention regulation, and including these patients could introduce heterogeneity in outcomes, making it difficult to assess the true effect of the intervention on attention-related symptoms; (c) studies that include both healthy participants and children with ADHD, but data for ADHD patients is not reported separately; (d) studies that report only the feasibility of BCI-based interventions without any treatment outcomes; and (e) studies that focus solely on nonmedical outcomes of BCI interventions, such as effects on social interactions or economic aspects.

Study Selection and Data Extraction

First, two authors independently screened the titles and abstracts of the studies identified from the electronic sources based on the inclusion criteria. Second, two authors independently screened the full texts of the studies based on the exclusion criteria. Finally, each included study was independently extracted by two authors for the following data: Study details (author name, year, setting and country, design, and duration), participant details (including age, sex, and treatment plan), and outcomes (primary and secondary). Any conflict between the two independent authors was resolved by the mutual consensus of all authors.

Risk of Bias Assessment

The risk of bias for RCTs was assessed using RoB 1 developed by Cochrane Collaboration (Higgins et al., 2011). It has seven domains that assess selection, performance, detection, attrition, reporting, and other biases. In each domain, the risk of bias was marked as low, uncertain, or high. The risk of bias for nonrandomized studies was assessed using the methodological index for nonrandomized studies (MINORS) tool developed by Slim et al. (2003). It has a general section with eight criteria for the rating of aims, sampling, planning, endpoints, outcome assessment, follow-up period, attrition, and sample size calculation, respectively. There is an additional section only for comparative studies with four criteria for the rating of control group adequacy, contemporariness of groups, baseline equivalence, and statistical analysis, respectively. On each criterion, the study can be rated 0 (*not reported*), 1 (*inadequately reported*), and 2 (*adequately reported*). The overall maximum score is 16 for noncomparative and 24 for comparative studies.

Statistical Analysis

The data for all outcomes was summarized qualitatively. To evaluate the improvement in the symptoms of ADHD (represented by changes in ADHD-RS and IVA-CPT scores), a pooled analysis using inverse variance (IV) method and fixed-effects model was conducted. Heterogeneity was assessed by Cochrane Q and I2 tests. All analysis was performed with RevMan Web. No sensitivity analysis and assessment of publication bias was performed.

Results

Characteristics and Bias Assessment of Included Studies

A total of 4,103 records were identified through the database search and the manual search. The duplicates were removed, and the remaining 3,260 records underwent title-and-abstract screening. Out of these, 3,236 records were excluded and 26 records were selected for full-text screening. Eleven studies were finally included in the review. The whole screening process is summarized in the PRISMA 2009 flow diagram (Figure 1). Studies excluded in secondary screening along with reasons of exclusion are given in Table 2A.

The included studies, published between 2008 and 2023, reported the data on ADHD patients from three double-arm intervention-control RCTs (Johnstone et al., 2017; Lim et al., 2019; Qian et al., 2018), one double-arm comparative RCT (Lim et al., 2023), one control-matched single-arm trial (Lim et al., 2010), and six single-arm trials (Blandón et al., 2016; Georgiou et al., 2019; Lim et al., 2012; Liu et al., 2013; Park et al., 2019; Yan et al., 2008). One RCT, Johnstone 2017 (Johnstone et al., 2017), had two subgroups with one comprising of ADHD patients with a confirmed diagnosis of ADHD and the other of patients with subclinical symptoms. Only the data from the former group was collected for this review. The characteristics of the included studies are summarized in Table 3A and the patient characteristics are given in Table 2.

Figure 1. *PRISMA flowchart for the Screening Process.*

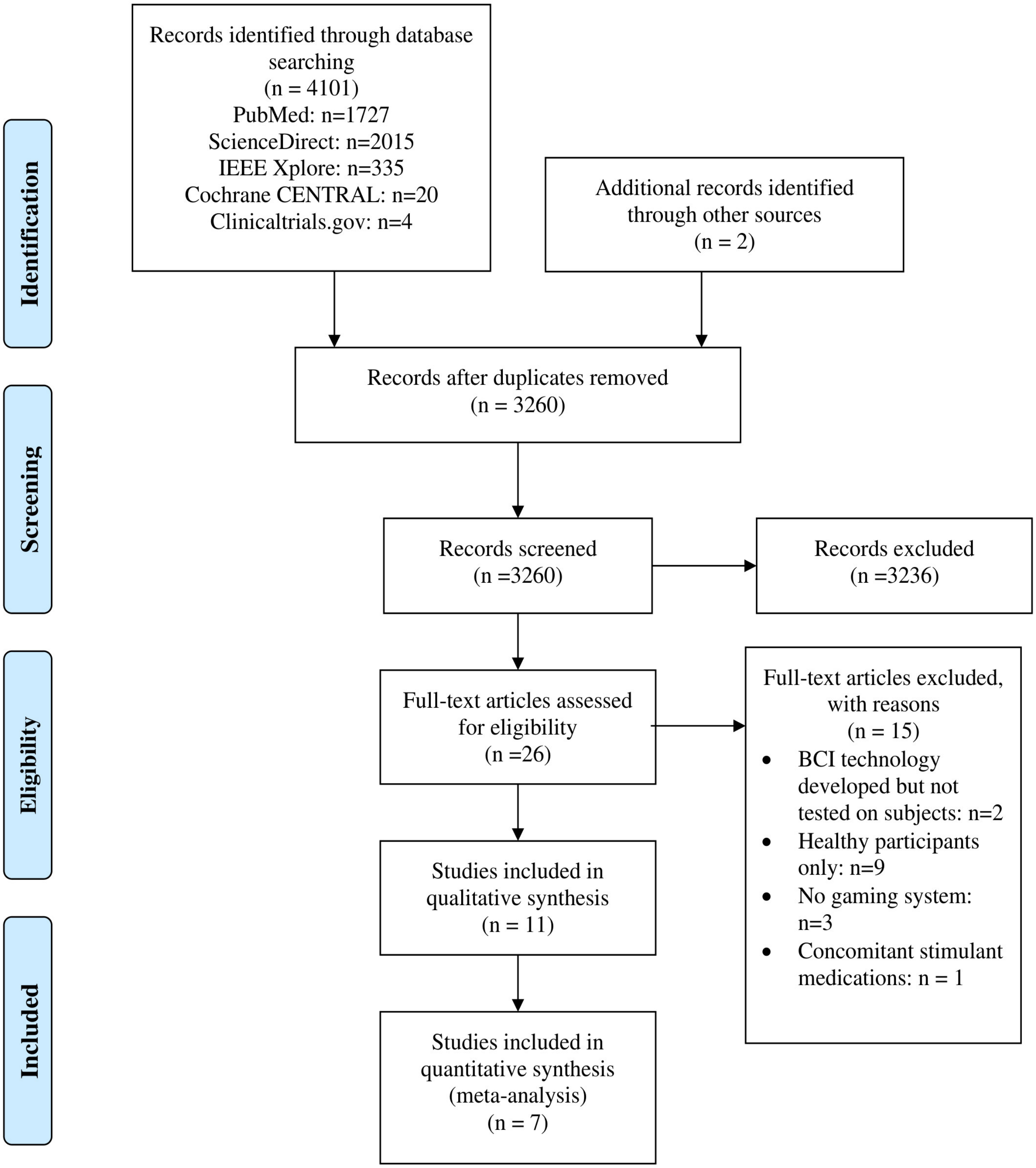


Table 2
Patient Characteristics and BCI Games Used in the Eleven Included Studies

Study ID	Total number of participants	Type of BCI	Age range/ Mean age	Gender distribution	Comorbidities	Groups	
						BCI	Non-BCI
Blandón et al. (2016)	9 children	Active	5–12	N/A	None	9	-
Georgiou et al. (2019)	53 children	Active	9.98 ± 1.85	40 males 13 females	None	53	-
Johnstone et al (2017)	44 children	Active	9.81 / 7.3–12.8	31 males 13 females	None	22	22
Lim et al. (2010)	16 children	Active	8.9 ± 1.4	13 males 3 females	None	8	8
Lim et al. (2012)	20 children	Active	7.8 ± 1.4 / 6-11	16 males 4 females	None	20	-
Lim et al. (2019)	163 children	Active	8.6 ± 1.54 / 6–12	138 males 25 females	None	81	82
Lim et al. (2023)	20 children (10 home-based and 10 in clinic)	Active	9.93 ± 1.69 / 6–12	16 males 4 females	Tourette syndrome, dyslexia	20	-
Liu et al. (2013)	13 children	Active	6–13 years	19 males 3 females	None	13	
Park et al. (2019)	5 children	Passive	6–8	All males	None	5	-
Qian et al. (2018)	66 children	Active	9.00 ± 1.50	All males	None	44	22
Yan et al. (2008)	12 children	Active	8–12 years	10 males 2 females	None	12	-

Available BCI-Based Equipment

All of the included studies utilized seven unique BCI-based intervention programs, which are summarized in Table 3. Based on the specific mode of interaction of the interface, the BCI equipment was classified into three categories (i.e., active, reactive, and passive). Only one of the included studies, Park et al. (2019) utilized passive BCI mode of interaction. The remaining eight studies utilized active BCI mode of interaction.

1. Lim et al. (2010) developed a puzzle game where users' attention levels were used to solve increasingly complex puzzles. EEG signals were collected via electrodes placed at Fp1, Fp2, and Pz, covering frequencies from 4 Hz to 36 Hz, including theta, alpha, beta 1, and beta 2 waves. These signals were processed through spatial filters, and machine learning was applied to classify the EEG data into attention or nonattention states, providing a quantifiable attention score. Calibration of the BCI system was achieved using EEG data collected during a concentration task involving the game.
2. Subsequent studies by Lim (2012, 2019, 2023) and Qian et al. (2018) involved a 3D computerized graphic game named *CogoLand*. In this game, participants controlled an avatar based on EEG signals detected by electrodes placed at Fp1 and Fp2. The frequency bands (4–36 Hz) and signal processing techniques were consistent with those used in the previous puzzle game. The EEG data were computed into a BCI ADHD Severity Measure (BASM) score via a built-in regression function and presented to the user on screen. BCI calibration was done using EEG waves recorded during a color Stroop test.
3. Blandón et al. (2016) created a virtual reality (VR) adventure game called *Harvest Challenge*, where players interacted with virtual objects by modulating their attention levels. This study utilized two toolboxes: HCI-signal processing toolbox for

processing physiological and biomechanical signals, including electromyographic (EMG) signals, and NeuroRead for EEG signal processing and visualization from low-cost BCI systems. The frequency bands recorded ranged from 0.5 Hz to 35 Hz, covering alpha, beta, delta, theta, and gamma waves. These attention levels were mapped from 0 to 100 percent, providing visually explicit physiological feedback.

4. Johnstone et al. (2017) developed *Focus Pocus*, a game consisting of 14 mini-games, including 6 NF games. Out of these, two games focused on attention, two on relaxation, and two on zen feedback. A portable EEG device collected waves in delta, theta, alpha, and beta frequency bands. Proprietary algorithms calculated values representing two independent psychological states: "attention" and "relaxation," with scores presented between 0 and 100.
5. Georgiou et al. (2019) utilized the *FocusLocus* game system, where players expand a reef colony by employing tactics and strategic planning skills such as goal setting, planning, sequencing, and time management. EEG waves were collected and clustered into five frequency bands corresponding to brainwaves: (a) delta waves (0.5 Hz to 3 Hz), (b) theta waves (4 Hz to 7 Hz), (c) alpha waves (8 Hz to 13 Hz), (d) beta waves (14 Hz to 30 Hz), and (e) gamma waves (31 Hz to 50 Hz).
6. Park et al. (2019) developed a passive mode BCI game with an immersive fairy tale experience. Users followed the storyline and read dialogues on the screen while the BCI system monitored their brain and motion activity. The game adapted its gameplay by prolonging time or incorporating encouraging words from game characters if the user's attention level dropped.
7. Yan et al. (2008) and Liu et al. (2013) developed a series of games that integrate NF and VR technologies, allowing patients' attention levels to influence gameplay. For instance, Yan et al. (2008) described a game where a player's attention controls the movement of a spaceship. The spaceship accelerates when the EEG-based BCI detects an increase in the player's attention level.

Table 3

Specification of the Seven BCI-Based Games

Name of the game	BCI mode (active/ passive)	Control interface	Gameplay	Mechanism of levels	Duration per session
Puzzle Game (Cogoland initial version)	Active	EEG (alpha, beta 1, and beta 2 waves)	Puzzle game / a series of games with increasing difficulty.	N/A	Two 30-min sessions/week for 10 weeks
Cogoland	Active	The EEG data was collected via a headband with two dry EEG sensors (4–36 Hz).	Adventure game with different levels. The player has to cover as much distance as possible in the first level and then collect fruits in the subsequent levels.	There were three levels in the game and each level required additional attention to play.	Three 30-min sessions/week for 8 weeks
Harvest Challenge	Active	NeuroRead v1.1 was utilized, which is a toolbox for EEG processing (alpha, beta, delta & theta waves) and visualization.	The game starts in an ecological farm and the first task is to collect the equipment needed for a safe ride in the canopy. Next, the player is given the task to repair the pathway and collect as many carrots as possible.	Three levels in total: 1. Equipment for the Canopy 2. Repairing the pathway 3. Harvesting the carrots The previous level has to be cleared first in order to reach the next level.	30 min/session, total two sessions

Table 3
Specification of the Seven BCI-Based Games

Name of the game	BCI mode (active/ passive)	Control interface	Gameplay	Mechanism of levels	Duration per session
Focus Pocus	Active	The portable, dry sensor “Mindwave” EEG device was used. The EEG waves were alpha, beta, delta & theta waves.	The player is a “wizard in training” working to improve important wizard skills such as broomstick racing, transformation, potion making, etc.	In each training session, two NF games were driven by Attention, two by Relaxation, and two by Zen feedback.	3-4 sessions/week, total of 25 sessions over 6–8 weeks
FocusLocus	Active	EEG was recorded via a wearable headset equipment. The recorded waves were alpha, beta, gamma, delta, and theta.	Well-established paradigms of Real-Time Strategy (RTS) and Management Simulation (MS) game genres.	The game includes rewards and punishments that will be offered to the player on the basis of their performance.	No more than 30 min/session.
Fairy-Tale game	Passive	The control interface “Adaptive Behavior Training Game Platform (ABTGP)” collects brainwaves as EEG.	The player acts as a third character in the story of a fisherman and a genie. The player is given tasks and if his attention drops, the fisherman encourages him to carry out tasks.	No levels, increased concentration required to perform subsequent tasks.	37-min runtime, sessions performed over 5 weeks, including one 20-min adaptation test and four 40-min full tests
Virtual Environment (VE) games	Active	EEG signals (0.1–70 Hz) collected via electrodes placed on scalp	Three spaceships move on computer screen. The middle spaceship speeds up in response to an inspirational signal from EEG	N/A	25- to 35-min sessions performed twice per week with total 20 training sessions

Symptom Reduction

ADHD-RS Scores. Five of the included studies reported ADHD-RS IA and HI scores (except for Johnstone et al. (2017), which reported a modified scale consisting of questions from both these sheets) reported by a parent, teacher or a clinician. The summary of these scores is given in Table 4A. The pooled analysis using IV method and the fixed-effects model using two of the included intervention-control RCTs, Lim et al. (2010 & 2019), showed a statistically significant mean difference between intervention and control groups in parent-reported (*MD* = 2.2; 95% CI: 0.91–3.49; *P* = .0008) as well as clinician-reported (*MD* = 1.6; 95% CI: 0.32–2.88; *P* = .001) IA scores. The pooled scores and the analyses are presented in Figure 2.

Furthermore, the pooled pre- and postintervention values from five of the included trials (Lim et al., 2010, 2012, 2019, 2023; Qian et al., 2018), using IV method and the fixed-effects model, showed statistically significant improvements in the parent-reported (*MD* = 3.7; 95% CI: 2.11–5.29; *P* < .00001) and the clinician-reported (*MD* = 3.20; 95% CI: 1.82–4.58; *P* < .00001) ADHD-RS IA scores. The analyses are presented in Figure 3. Similarly, the pooled pre- and postintervention values for parent-reported ADHD-RS HI score with the same methods showed a statistically significant difference (*MD* = 3.88; 95% CI: 1.88–5.87; *P* < .0001). The analysis is presented in Figure 4.

Integrated Visual and Auditory Continuous Performance Test (IVA-CPT) Scores. Two studies, Yan et al. (2008) and Liu et al. (2013), utilized the IVA-CPT to assess changes in response control and attention quotients, along with their auditory and visual components (see Table 5A).

Figure 2. *Forest Plot of Pooled MD for ADHD-RS IA Scores.*

	Intervention			Control/ waitlist				Mean difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Fixed, 95% CI**
1.1.1 Parent-reported								
Lim 2010	3	4.8	8	0.8	1.3	8	13.9%	2.20 [-1.25 , 5.65]
Lim 2019	4	4.8	81	1.8	4.21	82	86.1%	2.20 [0.81 , 3.59]
Subtotal (95% CI)			**89**			**90**	**100.0%**	**2.20 [0.91 , 3.49]**
Heterogeneity: Chi² = 0.00, df = 1 (P = 1.00); I² = 0%								
Test for overall effect: Z = 3.35 (P = 0.0008)								
1.1.2 Teacher-reported								
Lim 2010	6	5.9	5	0.8	5.6	6	100.0%	5.20 [-1.64 , 12.04]
Subtotal (95% CI)			**5**			**6**	**100.0%**	**5.20 [-1.64 , 12.04]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.49 (P = 0.14)								
1.1.3 Clinician-reported								
Lim 2019	3.5	3.87	81	1.9	4.42	81	100.0%	1.60 [0.32 , 2.88]
Subtotal (95% CI)			**81**			**81**	**100.0%**	**1.60 [0.32 , 2.88]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 2.45 (P = 0.01)								

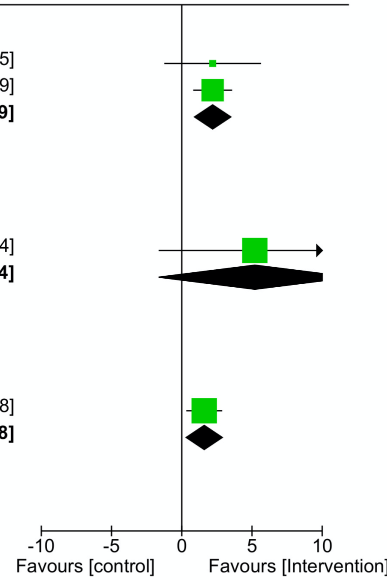


Figure 3. *Forest Plot of Pooled MD for Pre- and Postintervention ADHD-RS IA Scores.*

	Pre-intervention			Post-intervention				Mean difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Fixed, 95% CI**
2.1.1 Parent-reported								
Lim 2010	18	6.1	8	15	5.9	8	7.3%	3.00 [-2.88 , 8.88]
Lim 2012	17.7	5	20	12.6	3.4	20	36.0%	5.10 [2.45 , 7.75]
Qian 2018	16.27	4.25	18	13.16	4.07	18	34.2%	3.11 [0.39 , 5.83]
Lim 2023	15.9	6.97	10	14.1	6.31	10	7.4%	1.80 [-4.03 , 7.63]
Lim 2023	17.7	4.32	10	14.7	4.97	10	15.2%	3.00 [-1.08 , 7.08]
Subtotal (95% CI)			**66**			**66**	**100.0%**	**3.70 [2.11 , 5.29]**
Heterogeneity: Chi² = 1.83, df = 4 (P = 0.77); I² = 0%								
Test for overall effect: Z = 4.57 (P < 0.00001)								
2.1.2 Teacher-reported								
Lim 2010	6	5.9	5	0.8	5.6	5	100.0%	5.20 [-1.93 , 12.33]
Subtotal (95% CI)			**5**			**5**	**100.0%**	**5.20 [-1.93 , 12.33]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.43 (P = 0.15)								
2.1.3 Clinician-reported								
Lim 2019	18.9	4.25	78	15.6	5.26	78	84.3%	3.30 [1.80 , 4.80]
Lim 2023	17.9	5.61	10	14.7	4.97	10	8.8%	3.20 [-1.45 , 7.85]
Lim 2023	16.1	5.69	10	14.1	6.3	10	6.9%	2.00 [-3.26 , 7.26]
Subtotal (95% CI)			**98**			**98**	**100.0%**	**3.20 [1.82 , 4.58]**
Heterogeneity: Chi² = 0.22, df = 2 (P = 0.90); I² = 0%								
Test for overall effect: Z = 4.55 (P < 0.00001)								

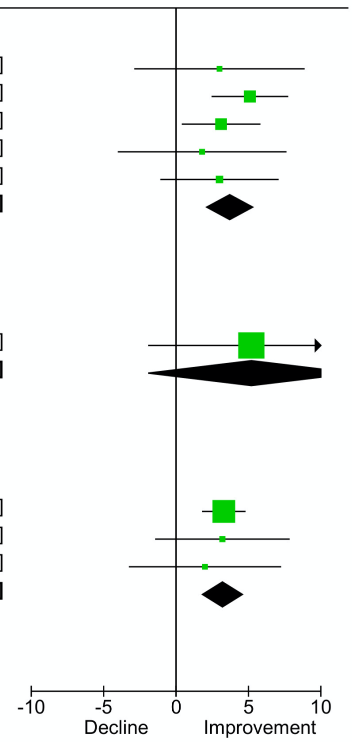
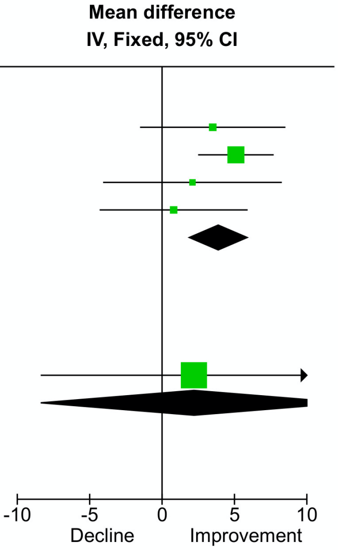


Figure 4. *Forest Plot of Pooled MD for Pre- and Postintervention ADHD-RS HI Scores.*

Study or Subgroup	Pre-intervention Mean	Pre-intervention SD	Pre-intervention Total	Post-intervention Mean	Post-intervention SD	Post-intervention Total	Weight	Mean difference IV, Fixed, 95% CI
2.2.1 Parent-reported								
Lim 2010	14.9	5.6	8	11.4	4.6	8	15.8%	3.50 [-1.52 , 8.52]
Lim 2012	15.6	3.9	19	10.5	4.3	19	58.5%	5.10 [2.49 , 7.71]
Lim 2023	11.8	8.44	10	9.7	5.29	10	10.5%	2.10 [-4.07 , 8.27]
Lim 2023	12.2	5.37	10	11.4	6.26	10	15.3%	0.80 [-4.31 , 5.91]
Subtotal (95% CI)			**47**			**47**	**100.0%**	**3.88 [1.88 , 5.87]**
Heterogeneity: Chi² = 2.58, df = 3 (P = 0.46); I² = 0%								
Test for overall effect: Z = 3.81 (P = 0.0001)								
2.2.2 Teacher-reported								
Lim 2010	16.8	9.3	5	14.6	7.7	5	100.0%	2.20 [-8.38 , 12.78]
Subtotal (95% CI)			**5**			**5**	**100.0%**	**2.20 [-8.38 , 12.78]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.41 (P = 0.68)								



A pooled analysis of pre- and postintervention values from these studies, using the IV method and a fixed-effects model, revealed statistically significant increases. Specifically, the overall auditory RCQ increased (*MD* = 12.18, 95% CI: 4.93–19.42; *P* = .001), as did the visual RCQ (*MD* = 10.68, 95% CI: 2.15–19.20; *P* = .01) and the overall RCQ (*MD* = 12.85, 95% CI: 6.01–19.68; *P* = .0002). Similarly, for the attention quotient, there were significant increases in auditory AQ (*MD* = 17.29, 95% CI: 8.76-25.81; *P* < .001), visual AQ (*MD* = 22.48, 95% CI: 13.33–31.73; *P* < .00001), and overall AQ (*MD* = 22.93, 95% CI: 15.44–30.43; *P* < .00001). The analyses are given in Figure 5 and Figure 6.

Figure 5. *Forest Plot of Pooled MD for Pre- and Postintervention Response Control Quotient Scores.*

Study or Subgroup	post-intervention Mean	post-intervention SD	post-intervention Total	pre-intervention Mean	pre-intervention SD	pre-intervention Total	Weight	Mean difference IV, Fixed, 95% CI
2.3.1 Auditory score								
Liu 2013	98.571	7.208	13	86.357	17.372	13	50.2%	12.21 [1.99 , 22.44]
Yan 2008	97.286	10.095	12	85.143	15.082	12	49.8%	12.14 [1.87 , 22.41]
Subtotal (95% CI)			**25**			**25**	**100.0%**	**12.18 [4.93 , 19.42]**
Heterogeneity: Chi² = 0.00, df = 1 (P = 0.99); I² = 0%								
Test for overall effect: Z = 3.29 (P = 0.0010)								
2.3.2 Visual score								
Liu 2013	96.714	10.179	13	83.929	17.394	13	60.6%	12.78 [1.83 , 23.74]
Yan 2008	94.571	13.636	12	87.143	19.777	12	39.4%	7.43 [-6.16 , 21.02]
Subtotal (95% CI)			**25**			**25**	**100.0%**	**10.68 [2.15 , 19.20]**
Heterogeneity: Chi² = 0.36, df = 1 (P = 0.55); I² = 0%								
Test for overall effect: Z = 2.45 (P = 0.01)								
2.3.3 Overall								
Liu 2013	97.286	6.9	13	83.216	16.172	13	51.1%	14.07 [4.51 , 23.63]
Yan 2008	95.857	9.685	12	84.29	14.291	12	48.9%	11.57 [1.80 , 21.33]
Subtotal (95% CI)			**25**			**25**	**100.0%**	**12.85 [6.01 , 19.68]**
Heterogeneity: Chi² = 0.13, df = 1 (P = 0.72); I² = 0%								
Test for overall effect: Z = 3.69 (P = 0.0002)								

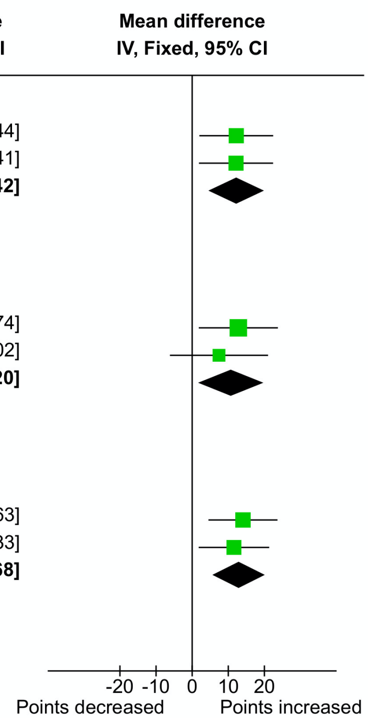
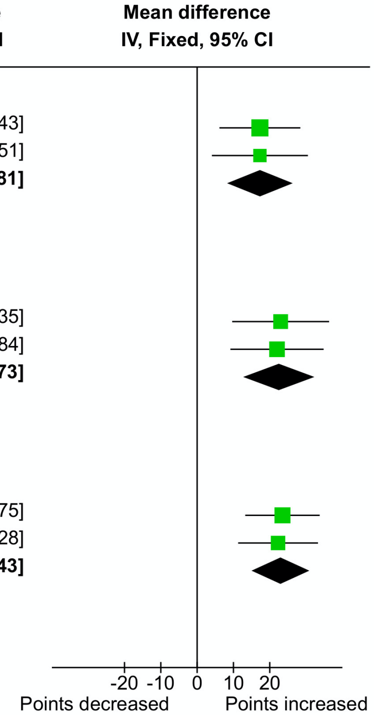


Figure 6. *Forest Plot of Pooled MD for Pre- and Postintervention Attention Quotient Scores.*

Study or Subgroup	post-intervention Mean	SD	Total	pre-intervention Mean	SD	Total	Weight	Mean difference IV, Fixed, 95% CI
2.4.1 Auditory score								
Liu 2013	91.857	9.115	13	74.571	18.364	13	58.5%	17.29 [6.14 , 28.43]
Yan 2008	96.572	16.257	12	79.286	16.799	12	41.5%	17.29 [4.06 , 30.51]
Subtotal (95% CI)			**25**			**25**	**100.0%**	**17.29 [8.76 , 25.81]**
Heterogeneity: Chi² = 0.00, df = 1 (P = 1.00); I² = 0%								
Test for overall effect: Z = 3.98 (P < 0.0001)								
2.4.2 Visual score								
Liu 2013	95.143	11.408	13	72.143	21.746	13	48.0%	23.00 [9.65 , 36.35]
Yan 2008	90.857	11.098	12	68.857	19.786	12	52.0%	22.00 [9.16 , 34.84]
Subtotal (95% CI)			**25**			**25**	**100.0%**	**22.48 [13.23 , 31.73]**
Heterogeneity: Chi² = 0.01, df = 1 (P = 0.92); I² = 0%								
Test for overall effect: Z = 4.76 (P < 0.00001)								
2.4.3 Overall								
Liu 2013	94.071	8.325	13	70.572	16.928	13	53.5%	23.50 [13.24 , 33.75]
Yan 2008	93.429	12.012	12	71.143	15.279	12	46.5%	22.29 [11.29 , 33.28]
Subtotal (95% CI)			**25**			**25**	**100.0%**	**22.93 [15.44 , 30.43]**
Heterogeneity: Chi² = 0.03, df = 1 (P = 0.87); I² = 0%								
Test for overall effect: Z = 5.99 (P < 0.00001)								



Clinical Global Impression-Severity (CGAS) and Children Global Assessment Scale (CGI-S) Scores. Only two RCTs, Lim et al. (2019) and Lim et al. (2023), reported clinician-assessed CGAS and CGI-S scores. Lim et al. (2019) reported a statistically significant mean difference (*MD* = 3.3; 95% CI: 2.4–4.2; *P* < .0001) and (*MD* = 4.5; 95% CI: 3.5–5.4; *P* < .0001) between the intervention and the waitlist at the 20th and 24th week of intervention compared to mean change at 8th week of waitlist, respectively. Similar results were reported for the clinician-rated CGI-S scores for the two groups. On the other hand, Lim et al. (2023) reported the group differences in CGAS and CGI-S scores between the children receiving home-based and clinic-based intervention. However, no significant differences were observed in those scores. The results from these studies are summarized in Table 4.

Behavioral Enhancement

Child Behavior Checklist (CBCL) Scores. Three of the included studies, Qian et al. (2018), Lim et al. (2019), and Lim et al. (2023), reported behavioral enhancement in the form of improvements on various versions of parent-reported CBCL scales. Two of the studies reported the mean values and measures of variance for intervention and waitlist groups, while one RCT, Lim et al. (2023), compared home-based intervention against clinic-based intervention. The reported findings from these three are summarized in Table 5.

Reading Disability. Only one study, Park et al. (2019), reported improvement in reading comprehension (reciting, vocabulary understanding, sentence completion, vocabulary selection, sentence structure, short passage reading comprehension) on the Korean National Intelligence for Special Education–Basic Academic Achievement Test (KNISE-BAAT) scale, showing a statistically significant improvement in reciting short passage comprehension (*P* = .021) and general reading comprehension (Park et al., 2019).

Brain Function Modulation

Only one study, Qian et al. (2018), reported the analysis of functional and structural MRI images pre- and postinterventions. Global efficiency and clustering coefficient did not show any significant effect of the BCI-based training over time (*P* > .05). In contrast, the small-worldness measure showed a significant time and group interaction (*P* = .045). After the BCI-based training, the small-worldness of the intervention group remained almost the same while that of the control group decreased significantly. Moreover, the reduction of small-worldness was correlated with less behavioral improvement (CBCL internalizing problems) over time across all ADHD patients (*r* = −0.384, *P* = .040).

Table 4
CGAS and CGI-S Scores for the Intervention and Control Groups

Study ID	Assessor	Test	Time of assessment	Intervention group Mean change from baseline (*SD*)	Control group Mean change from baseline (*SD*)	Group Difference reported *MD* (*SD*); *P* value
Lim et al. (2019)	Clinician	CGAS	at Week 8	2.8 (4.75)	1.8 (4.92)	1.03 (−2.6–0.5) *P* = .1817
			at Week 20	3.2 (6.03)	N/A	3.3 (2.4–4.2) *P* < .0001
			at Week 24	4.3 (5.87)	N/A	4.5 (3.5–5.4) *P* < .0001
	Clinician	CGI-S	at Week 8	Median Change = 0.0; Range = (−5.0, 1.0)	Median Change = 0.0; Range = (−1.0, 2.0)	Median D (Range) = 0.0; *P* = .2026
			at Week 20	Median Change = 0.0; Range = (−2.0, 5.0)		Median D (Range) = 0.0 (−2.0, 5.0); *P* < .0001
			at Week 24	Median Change = 0.0; Range = (−2.0, 5.0)		Median D (Range) = 0.0 (−2.0, 5.0); *P* < .0001
Lim et al. (2023)	Clinician	CGAS	At week 8	3.70 (7.88)	5.56 (3.68)	*P* = .68
[The intervention is clinic and the control is home]	Clinician	CGI-S	At week 8	−0.06 (0.70)	−0.50 (0.53)	*P* = .28

Adverse Effects

Two of the included studies, Lim et al. (2019) and Lim et al. (2023), reported treatment-associated adverse events. Lim et al. (2019) stated that a total of 6.4% (11/172) participants reported at least one adverse event, and headache was the most common complaint, followed by dizziness (6 and 4, respectively). Only one participant reported two different adverse events on one occasion, i.e., headache and trouble paying attention or concentrating. Lim et al. (2023) stated that only 2 out of 20 participants reported to have experienced a side effect. None of these adverse events required medical treatment or were rated to be severe.

Risk of Bias Assessment

The risk of bias of nonrandomized studies assessed with MINORS is given in Table 6A. The only comparative study, Lim et al. (2010), scored 19 which indicates high risk of bias (ideal score = 24). Four noncomparative ones scored 11 or above, and two, Blandón et al. (2016) and Liu et al. (2013), scored 7 points, indicating high risk of bias in all these studies. The risk of bias for only single arm studies using is presented in Figure 7. The risk of bias of RCTs assessed with RoB 1 is given in Figure 8. All studies but Johnstone et al. (2017) had a low risk of bias in majority of the domains.

Table 5
CBCL Scores for Intervention and Control Groups

Study ID	Assessor	CBCL type	Time of assessment	Intervention group		Control group	
				Mean (*SD*)	**Mean Difference (*SD*)**	**Mean (*SD*)**	**Mean Difference (*SD*)**
Qian et al. (2018)	Parents	Internalizing problems	Baseline	7.88 (5.08)		12.36 (9.65)	
			At week 8	5.38 (4.17)		10.54 (7.84)	
Lim et al. (2019)	Parent	Internalizing problems	Baseline	61.2 (10.1)		60.9 (10.59)	
			At week 8	N/A	Baseline/week 8 = 4.0 (4.80)		Baseline/week 8 = 1.8 (4.21)
			At week 20	N/A	Baseline/week 20 = 4.1 (5.59)		
			At week 24	N/A	Baseline/week 24 = 5.3 (6.17)		
		Externalizing problems	Baseline	62.5 (9.45)		64.6 (9.19)	
			At week 8	N/A	Baseline/week 8 = 3.3 (6.54)		Baseline/week 8 = 2.5 (6.51)
			At week 20	N/A	Baseline/week 20 = 3.7 (8.20)		
			At week 24	N/A	Baseline/week 24 = 4.7 (8.70)		
Lim et al. (2023) [The intervention is clinic and the control is home]	Parent	Attention problems	Baseline	67.3 (10.0)		75.8 (12.9)	
			At week 8	N/A	Baseline/ week 8 = −3.70 (8.11)	N/A	Baseline/week 8 = −5.00 (7.82)
		Internalizing problems	Baseline	54.3 (10.9)		62.0 (7.56)	
			At week 8	N/A	Baseline/ week 8 = −3.10 (7.88)	N/A	Baseline/week 8 = −1.5 (7.09)
		Externalizing problems	Baseline	57.6 (12.1)		60.1 (10.10)	
			At week 8	N/A	Baseline/ week 8 = −3.60 (6.22)	N/A	Baseline/week 8 = −2.70 (5.79)
		Total problems	Baseline	60.7 (9.42)		66.1 (6.44)	
			At week 8	N/A	Baseline/ week 8 = −3.8 (4.19)	N/A	Baseline/week 8 = −3.00 (5.06)
		ADH Problems	Baseline	64.9 (8.21)		67.4 (8.98)	
			At week 8	N/A	Baseline/ week 8 = −2.30 (5.46)	N/A	Baseline/week 8 = −1.90 (6.21)

Figure 7. *Risk of Bias Assessment of Single Arm Studies by MINOR Scale. (0 = Not Reported, 1 = Reported but Inadequate, 2 = Adequately Reported).*

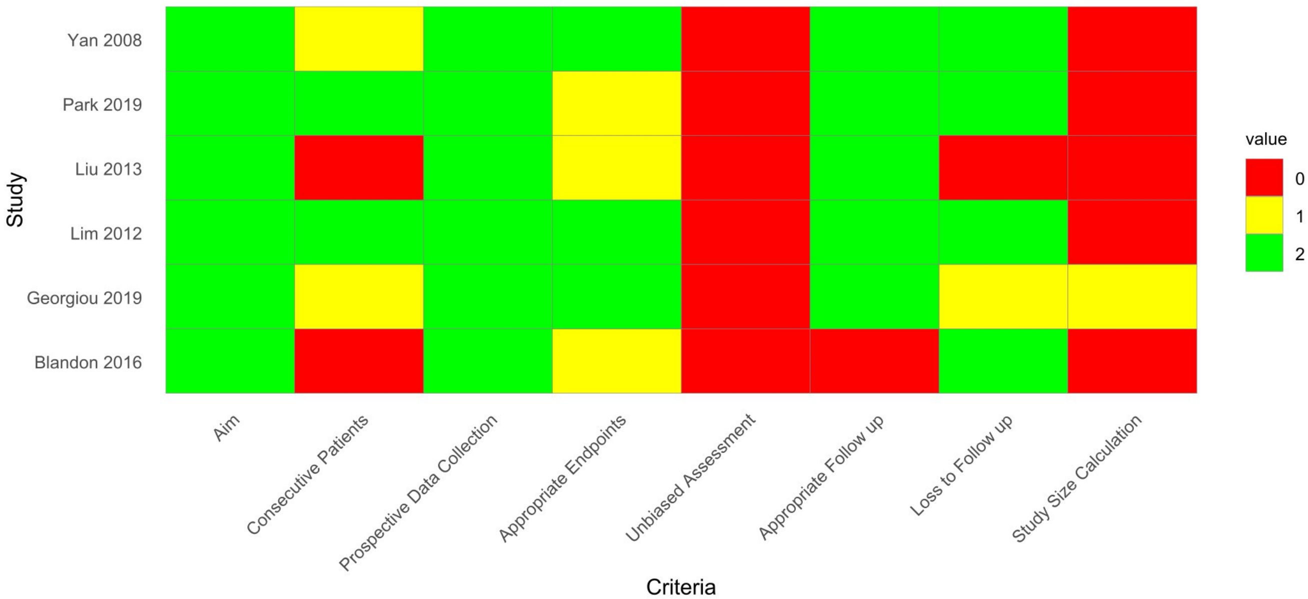
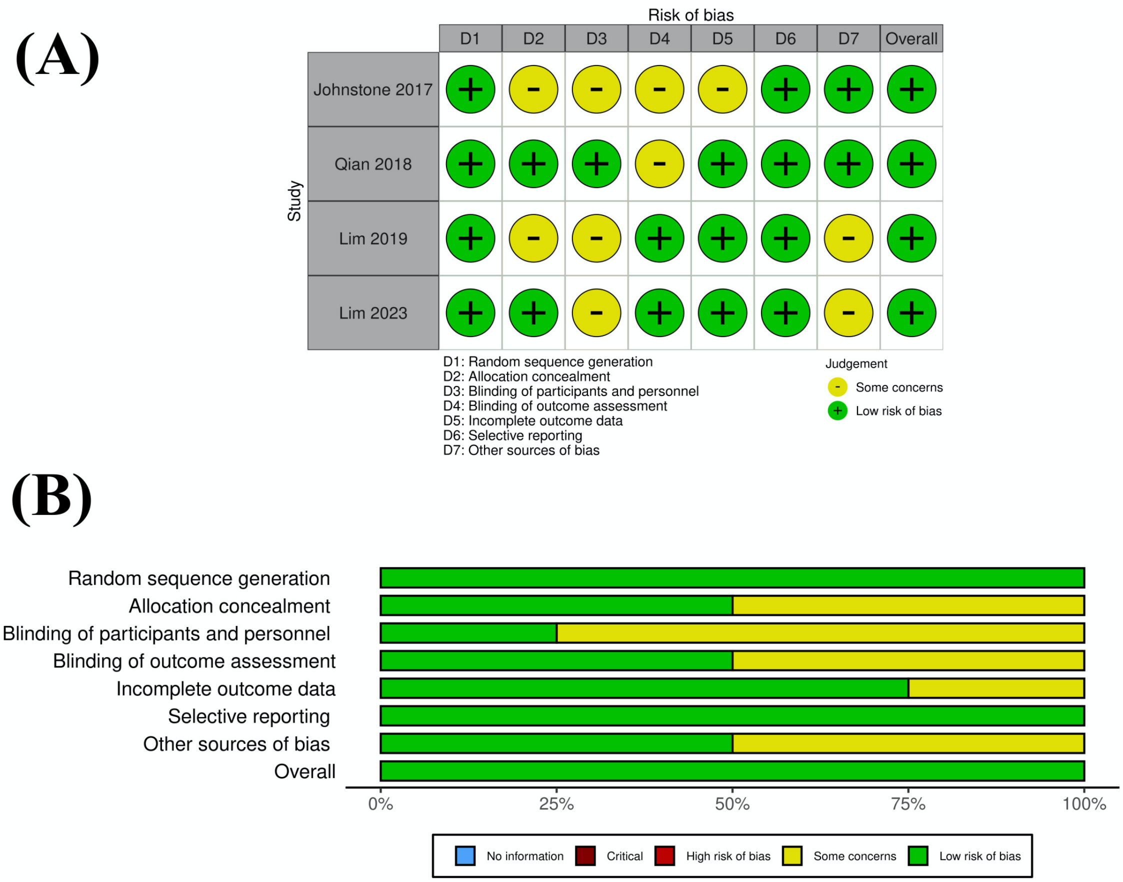


Figure 8. *Risk of Bias Assessment of RCTs by RoB 1 Scale. (A) Traffic Light Plot (B) Summary Plot.*



Discussion

The idea behind developing games for attention training in children with ADHD is to enhance their engagement with the treatment program (Strahler Rivero et al., 2015). These games also provide real-time feedback, helping children adapt more effectively (Strahler Rivero et al., 2015). Although only a few games have been tested on children with ADHD, six major game designs for attention training have been highlighted in this review. The most well-studied game is *CogoLand*, developed by a research team in Singapore. This game operates on the active BCI principle, using an EEG device to record brain waves (4–36 Hz) and employing waves associated with attentive states (beta 1 and beta 2) to control gameplay (Lim et al., 2012, 2019). In *CogoLand*, an avatar's movement speed on an island is proportional to the user's attention level (high frequency beta waves). Other games, such as *Harvest Challenge*, *Focus Pocus*, and *FocusLocus*, developed by research teams in Colombia, Australia, and Greece, respectively, also use active BCI techniques to control gameplay and provide feedback to the user (Blandón et al., 2016; Georgiou et al., 2019; Johnstone et al., 2017; Teo et al., 2021). In contrast, an immersive fairy tale game developed by a research team in Korea employs the passive BCI technique (Park et al., 2019). This game modifies itself based on unintentional changes in the user's brainwave activity, such as decreased attention levels, and adjusts the game in a way that subconsciously increases these levels (Park et al., 2019). While current data is insufficient to establish a definitive comparison between active and passive BCI-based games, theoretical frameworks suggest that active BCI games require continuous interaction and engagement from the user, making them potentially better for actively training and improving attention control. On the other hand, passive BCI games require less problem solving and interaction from the user, so they might be more suitable for users with moderate attention deficits requiring less demanding tasks for attention training. Also, this technique might be more appropriate for younger children (e.g., ages 1 to 5), as they can engage without the frustration of complex tasks while still promoting cognitive development through a supportive and nonintrusive approach. Future studies using passive BCI games should consider this point.

The included studies have reported the effects of these gaming systems on various outcomes in children with ADHD. For this review, changes in ADHD-RS scores were used as the primary criteria to assess symptomatic reduction in ADHD patients (DuPaul et al., 1998). A change-from-baseline analysis of studies using *CogoLand* revealed significant reductions in ADHD-RS IA and HI scores after 8–24 weeks of BCI training. Specifically, significant differences were observed between the intervention and control groups in their respective changes from baseline for IA scores. The games primarily target inattention symptoms, as individuals need to increase their attention levels to play. This explains the reduction in IA scores. Since this training induces neuroplastic changes in the brain, the strengthened neuronal networks also reduce HI symptoms as observed in these studies. The included studies whose data was pooled in the meta-analysis were conducted in similar settings using similar equipment and population (which may lower the generalizability of the results), and there was little heterogeneity. That is why sensitivity analysis and assessment of publication bias were deemed unnecessary.

One study by Johnstone et al. (2017), which used the *Focus Pocus* game, also reported lower postintervention ADHD-RS scores in the intervention group compared to the waitlist control group. Significantly decreased scores at timepoint 2 (7–9 weeks postintervention) indicate the efficacy of this device as well. Blandón et al. (2016) also reported increased attention levels in subsequent training sessions, measured by a built-in algorithm. All this data is promising enough to justify including these gaming systems in large prospective trials to determine their efficacy in symptom reduction more effectively.

Several studies have employed continuous performance tests (CPTs) to evaluate a subject's ability to respond to target stimuli while ignoring distractor stimuli through the execution of routine, automated tasks (Homack & Riccio, 2006). A modified version of this test, known as the IVA-CPT, presents stimuli on a computer screen: subjects must click the mouse in response to the target stimulus, a "1," and refrain from clicking in response to the distractor stimulus, a "2" (Sherman et al., 2023, p. 289). The two studies included in this review that performed this test to assess the effectiveness of BCI-based therapy demonstrated significant improvements in both the overall scores and the audio and visual components of the RCQ and AQ, the two primary quotient scores derived from this test (Liu et al., 2013; Yan et al., 2008). These findings suggest that BCI-based therapy enhances self-regulation by improving control over impulsivity and increasing consistency and endurance, as indicated by the improved RCQ scores. Additionally, the enhancement in AQ scores reflects the subjects’ increased ability to concentrate more effectively and sustain attention for longer periods after BCI-based therapy.

Other outcomes of efficacy included changes in the CGAS and CGI-S scores (Berk et al., 2008; Shaffer, 1983). The largest RCT utilizing BCI for ADHD, conducted by Lim et al. (2019), measured these scales and found significant differences from baseline at weeks 20 and 24, but not at the primary timepoint, week 8. This is likely because these scales are broader and assess improvements in general functioning, social interactions, and academic performance, which typically take more time to manifest. These improvements involve multiple areas of the child's life and require sustained changes in behavior and skills. However, the assessment of these scales is somewhat subjective as compared to the more objective ADHD-RS scale.

Learning disability (LD) is found in approximately 27 to 31 percent of students with ADHD (DuPaul & Volpe, 2009). The most common type of LD in children with ADHD is a reading disability, characterized by impaired phonological processing and comprehension problems (Purvis & Tannock, 2000). To assess the impact of BCI-based attention training on LD, Park et al. (2019) used an immersive fairy tale game. In this game, the dialogues of characters are written on the screen (with no audio), requiring the user to read them and make decisions. The results showed a significant improvement from baseline in reciting and reading comprehension of short passages, as determined by a standardized test on reading and comprehension (KINESE-BAAT). However, the study had a small sample size (*n* = 5) and included only three BCI sessions, so the findings may not be generalizable.

Improving a child's behavior is a key objective in ADHD management. Common behavioral symptoms in ADHD include noncompliance, lack of independence in completing daily chores, disorganization, aggression, and defiance toward parents (Pfiffner & Haack, 2014). To assess these behavioral symptoms, the included studies used CBCL (Nøvik, 1999). Internalizing problems are particularly important in the context of ADHD, as these comorbidities can significantly impact behavioral improvements in these children (Al-Yagon et al., 2020). Studies have reported a lower CBCL score postintervention, indicating a significant impact of BCI-based attention systems on behavioral enhancement. Specifically, studies by Qian et al. (2018), Lim et al. (2019), and Lim et al. (2023), all reported reductions in internalizing problems following BCI-based attention training compared to baseline. Given that the CBCL is a broad-scale assessment, the reported improvements after BCI-based training warrant further exploration to better understand the scope and mechanisms of these behavioral changes.

Brain EEG patterns are known to be altered in ADHD patients. In the study by Georgiou et al. (2019), the theta-beta ratio (TBR) was calculated before and after intervention. The findings indicated a decrease in TBRs following attention training, suggesting that the brain patterns were shifting more towards an attention state. This reduction in the TBR implies an improvement in attention-related brain activity, aligning with the goal of the training to enhance attentional control (Georgiou et al., 2019). Further evidence of brain function modulation is provided by Qian et al. (2018), who used neuroimaging with fMRI to study the effects of BCI-based attention training in children. The aim of the training was to decrease intranetwork connectivity while increasing internetwork connectivity to enhance global brain efficiency and reduce local efficiency. By increasing connectivity within the salience/ventral attention network (SVN) and between the SVN and other critical networks, the training appears to enhance the coordination between attention systems, which is crucial for managing ADHD symptoms. The reduction in connectivity between the SVN and subcortical networks suggests a potential normalization of brain function, addressing known deficits in dopaminergic signaling associated with ADHD (Cubillo et al., 2012; Li et al., 2014).

Small worldness is the property of brain network that describes a state with high clustering of neurons and shorter path lengths between two nodes (Bassett & Bullmore, 2017). Small world networks are associated with high attention states (Qi et al., 2021; Xu et al., 2015). In the study, Qian et al. (2018), the small-worldness measure showed a significant change over time (*P* = .045), indicating a difference in the brain network structure between the initial and final measurements. Furthermore, after the BCI-based training, the small-worldness of the intervention group remained relatively stable, while the small-worldness of the control group decreased significantly. This could imply that the BCI-based training helped maintain or preserve the brain's network structure in the intervention group.

Although BCI-based therapy appears promising, it's important to recognize that responses to the training are highly individualized, with some children benefiting more than others. All studies reviewed provided a structured training environment, raising the possibility that positive responses might be due to the structured setting rather than the BCI system itself. For example, Lim et al. (2019) noted that even the untreated control group showed reduced inattentive symptoms, a phenomenon referred to as the "halo effect." The single arm meta-analysis done for this review could not account for this effect as only pre- and postinterventional scores were compared and there was no control for comparison. These limitations, along with the overall high risk of bias of included studies, cast doubt on the generalizability of current findings. Future research should aim to more accurately evaluate the effectiveness of BCI-based therapy and develop models that integrate both inattention and learning disabilities into a single interface. More controlled trials that either compare this therapy to placebo or other therapies used for ADHD are also needed. Additionally, employing both active and passive BCI techniques could enhance training and maintain effectiveness.

Conclusion

Interventions involving BCI-based games help control the inattentive and hyperactive-impulsive symptoms of ADHD. They are also associated with behavior improvement, especially in regard to internalizing problems. Some evidence also suggests a beneficial role in managing learning disability, especially reading problems, in ADHD patients. Although these results are promising, future research should focus on simultaneously addressing inattention and learning disability in games in order to develop a more holistic BCI-based intervention for ADHD.

Author Disclosure

This review did not receive any funding or other financial support. The authors declare that they have no financial interest in any company or its competitors that develops or markets the games discussed in this review. The authors declare that they have no financial or personal interests that could be perceived as a conflict of interest in connection with this research.

References

Abarbanel, A. (1999). The neural underpinnings of neurofeedback training. In J. R. Evans & A. Abarbanel (Eds.), *Introduction to quantitative EEG and neurofeedback* (pp. 311–340). Academic Press. https://doi.org/10.1016/B978-012243790-8/50013-4

Adamou, M., Fullen, T., & Jones, S. L. (2020). EEG for diagnosis of adult ADHD: A systematic review with narrative analysis. *Frontiers in Psychiatry, 11*, Article 871. https://doi.org/10.3389/fpsyt.2020.00871

Al-Yagon, M., Forte, D., & Avrahami, L. (2020). Executive functions and attachment relationships in children with ADHD: Links to externalizing/internalizing problems, social skills, and negative mood regulation. *Journal of Attention Disorders, 24*(13), 1876–1890. https://doi.org/10.1177/1087054717730608

Arns, M., De Ridder, S., Strehl, U., Breteler, M., & Coenen, A. (2009). Efficacy of neurofeedback treatment in ADHD: The effects on inattention, impulsivity and hyperactivity: A meta-analysis. *Clinical EEG and Neuroscience, 40*(3), 180–189. https://doi.org/10.1177/155005940904000311

Ayano, G., Yohannes, K., & Abraha, M. (2020). Epidemiology of attention-deficit/hyperactivity disorder (ADHD) in children and adolescents in Africa: A systematic review and meta-analysis. *Annals of General Psychiatry, 19*(1), Article 21. https://doi.org/10.1186/s12991-020-00271-w

Bassett, D. S., & Bullmore, E. T. (2017). Small-world brain networks revisited. *The Neuroscientist, 23*(5), 499–516. https://doi.org/10.1177/1073858416667720

Berk, M., Ng, F., Dodd, S., Callaly, T., Campbell, S., Bernardo, M., & Trauer, T. (2008). The validity of the CGI severity and improvement scales as measures of clinical effectiveness suitable for routine clinical use. *Journal of Evaluation in Clinical Practice, 14*(6), 979–983. https://doi.org/10.1111/j.1365-2753.2007.00921.x

Blandón, D. Z., Muñoz, J. E., Lopez, D. S., & Gallo, O. H. (2016). Influence of a BCI neurofeedback videogame in children with ADHD. Quantifying the brain activity through an EEG signal processing dedicated toolbox. *2016 IEEE 11th Colombian Computing Conference (CCC)*, 1–8. https://doi.org/10.1109/ColumbianCC.2016.7750788

Bronte-Stewart, H. M., Petrucci, M. N., O'Day, J. J., Afzal, M. F., Parker, J. E., Kehnemouyi, Y. M., Wilkins, K. B., Orthlieb, G. C., & Hoffman, S. L. (2020). Perspective: Evolution of control variables and policies for closed-loop deep brain stimulation for Parkinson's disease using bidirectional deep-brain-computer interfaces. *Frontiers in Human Neuroscience, 14*, Article 353. https://doi.org/10.3389/fnhum.2020.00353

Carlson, C. L., Shin, M., & Booth, J. (1999). The case for DSM-IV subtypes in ADHD. *Mental Retardation and Developmental Disabilities Research Reviews, 5*(3), 199–206. https://doi.org/10.1002/(SICI)1098-2779(1999)5:3<199::AID-MRDD6>3.0.CO;2-#

Castellanos, F. X., & Proal, E. (2012). Large-scale brain systems in ADHD: Beyond the prefrontal-striatal model. *Trends in Cognitive Sciences, 16*(1), 17–26. https://doi.org/10.1016/j.tics.2011.11.007

Cervantes, J.-A., López, S., Cervantes, S., Hernández, A., & Duarte, H. (2023). Social robots and brain–computer interface video games for dealing with attention deficit hyperactivity disorder: A systematic review. *Brain Sciences, 13*(8), Article 8. https://doi.org/10.3390/brainsci13081172

Cubillo, A., Halari, R., Smith, A., Taylor, E., & Rubia, K. (2012). A review of fronto-striatal and fronto-cortical brain abnormalities in children and adults with attention deficit hyperactivity disorder (ADHD) and new evidence for dysfunction in adults with ADHD during motivation and attention. *Cortex, 48*(2), 194–215. https://doi.org/10.1016/j.cortex.2011.04.007

DuPaul, G. J., Power, T. J., Anastopoulos, A. D., & Reid, R. (1998). *ADHD Rating Scale—IV: Checklists, norms, and clinical interpretation* (pp. viii, 79). The Guilford Press.

DuPaul, G. J., & Volpe, R. J. (2009). ADHD and learning disabilities: Research findings and clinical implications.

Current Attention Disorders Reports, 1(4), 152–155. https://doi.org/10.1007/s12618-009-0021-4

Enriquez-Geppert, S., Smit, D., Pimenta, M. G., & Arns, M. (2019). Neurofeedback as a treatment intervention in ADHD: Current evidence and practice. *Current Psychiatry Reports, 21*(6), Article 46. https://doi.org/10.1007/s11920-019-1021-4

Georgiou, E., Thanos, K.-G., Kanellos, T., Doulgerakis, A., & Thomopoulos, S. (2019). Evaluating the relation between the EEG brainwaves and attention measures, and the children's performance in REEFOCUS game designed for ADHD symptoms improvement. In B. M. Cullum, D. Kiehl, & E. S. McLamore (Eds.), *Smart Biomedical and Physiological Sensor Technology XVI*, Proceedings Volume 11020. PIE Defense + Commercial Sensing. Baltimore, MD, USA. https://doi.org/10.1117/12.2518901

Gummadavelli, A., Zaveri, H. P., Spencer, D. D., & Gerrard, J. L. (2018). Expanding brain–computer interfaces for controlling epilepsy networks: Novel thalamic responsive neurostimulation in refractory epilepsy. *Frontiers in Neuroscience, 12*, Article 474. https://doi.org/10.3389/fnins.2018.00474

Higgins, J. P. T., Altman, D. G., Gøtzsche, P. C., Jüni, P., Moher, D., Oxman, A. D., Savović, J., Schulz, K. F., Weeks, L., & Sterne, J. A. C. (2011). The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ, 343*, Article d5928. https://doi.org/10.1136/bmj.d5928

Homack, S., & Riccio, C. A. (2006). Conners' Continuous Performance Test (2nd ed.; CCPT-II). *Journal of Attention Disorders, 9*(3), 556–558. https://doi.org/10.1177/1087054705283578

Jensen, C. M., Amdisen, B. L., Jørgensen, K. J., & Arnfred, S. M. H. (2016). Cognitive behavioural therapy for ADHD in adults: Systematic review and meta-analyses. *ADHD Attention Deficit and Hyperactivity Disorders, 8*(1), 3–11. https://doi.org/10.1007/s12402-016-0188-3

Johnstone, S. J., Roodenrys, S. J., Johnson, K., Bonfield, R., & Bennett, S. J. (2017). Game-based combined cognitive and neurofeedback training using focus pocus reduces symptom severity in children with diagnosed AD/HD and subclinical AD/HD. *International Journal of Psychophysiology, 116*, 32–44. https://doi.org/10.1016/j.ijpsycho.2017.02.015

Konrad, K., & Eickhoff, S. B. (2010). Is the ADHD brain wired differently? A review on structural and functional connectivity in attention deficit hyperactivity disorder. *Human Brain Mapping, 31*(6), 904–916. https://doi.org/10.1002/hbm.21058

Kovacevic, N., Ritter, P., Tays, W., Moreno, S., & McIntosh, A. R. (2015). 'My Virtual Dream': Collective neurofeedback in an immersive art environment. *PLoS ONE, 10*(7), Article e0130129. https://doi.org/10.1371/journal.pone.0130129

Li, F., He, N., Li, Y., Chen, L., Huang, X., Lui, S., Guo, L., Kemp, G. J., & Gong, Q. (2014). Intrinsic brain abnormalities in attention deficit hyperactivity disorder: A resting-state functional MR imaging study. *Radiology, 272*(2), 514–523. https://doi.org/10.1148/radiol.14131622

Lim, C. G., Lee, T. S., Guan, C., Fung, D. S. S., Zhao, Y., Teng, S. S. W., Zhang, H., & Krishnan, K. R. R. (2012). A brain-computer interface based attention training program for treating attention deficit hyperactivity disorder. *PLoS ONE, 7*(10), Article e46692. https://doi.org/10.1371/journal.pone.0046692

Lim, C. G., Lee, T.-S., Guan, C., Sheng Fung, D. S., Cheung, Y. B., Teng, S. S. W., Zhang, H., & Krishnan, K. R. (2010). Effectiveness of a brain-computer interface based programme for the treatment of ADHD: A pilot study. *Psychopharmacology Bulletin, 43*(1), 73–82.

Lim, C. G., Poh, X. W. W., Fung, S. S. D., Guan, C., Bautista, D., Cheung, Y. B., Zhang, H., Yeo, S. N., Krishnan, R., & Lee, T. S. (2019). A randomized controlled trial of a brain-computer interface based attention training program for ADHD. *PLoS ONE, 14*(5), Article e0216225. https://doi.org/10.1371/journal.pone.0216225

Lim, C. G., Soh, C. P., Lim, S. S. Y., Fung, D. S. S., Guan, C., & Lee, T.-S. (2023). Home-based brain–computer interface attention training program for attention deficit hyperactivity disorder: A feasibility trial. *Child and Adolescent Psychiatry and Mental Health, 17*(1), Article 15. https://doi.org/10.1186/s13034-022-00539-x

Liu, T., Wang, J., Chen, Y., Wang, R., & Song, M. (2013). Neurofeedback treatment experimental study for ADHD by using the brain-computer interface neurofeedback system. In M. Long (Ed.), *World congress on medical physics and biomedical engineering May 26–31, 2012, Beijing, China* (pp. 1537–1540). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-29305-4_404

Marzbani, H., Marateb, H. R., & Mansourian, M. (2016). Neurofeedback: A comprehensive review on system design, methodology and clinical applications. *Basic and Clinical Neuroscience, 7*(2), 143–158. https://doi.org/10.15412/J.BCN.03070208

Mridha, M. F., Das, S. C., Kabir, M. M., Lima, A. A., Islam, Md. R., & Watanobe, Y. (2021). Brain-computer interface: Advancement and challenges. *Sensors, 21*(17), Article 5746. https://doi.org/10.3390/s21175746

Nøvik, T. S. (1999). Validity of the child behaviour checklist in a Norwegian sample. *European Child & Adolescent Psychiatry, 8*(4), 247–254. https://doi.org/10.1007/s007870050098

Park, K., Kihl, T., Park, S., Kim, M.-J., & Chang, J. (2019). Fairy tale directed game-based training system for children with ADHD using BCI and motion sensing technologies. *Behaviour & Information Technology, 38*(6), 564–577. https://doi.org/10.1080/0144929X.2018.1544276

Peñuelas-Calvo, I., Jiang-Lin, L. K., Girela-Serrano, B., Delgado-Gomez, D., Navarro-Jimenez, R., Baca-Garcia, E., & Porras-Segovia, A. (2022). Video games for the assessment and treatment of attention-deficit/hyperactivity disorder: A systematic review. *European Child & Adolescent Psychiatry, 31*(1), 5–20. https://doi.org/10.1007/s00787-020-01557-w

Pfiffner, L. J., & Haack, L. M. (2014). Behavior management for school-aged children with ADHD. *Child and Adolescent Psychiatric Clinics of North America, 23*(4), 731–746. https://doi.org/10.1016/j.chc.2014.05.014

Piña, R., Rozas, C., Contreras, D., Hardy, P., Ugarte, G., Zeise, M. L., Rojas, P., & Morales, B. (2020). Atomoxetine reestablishes long term potentiation in a mouse model of attention deficit/hyperactivity disorder. *Neuroscience, 439*, 268–274. https://doi.org/10.1016/j.neuroscience.2019.10.040

Purvis, K. L., & Tannock, R. (2000). Phonological processing, not inhibitory control, differentiates ADHD and reading disability. *Journal of the American Academy of Child & Adolescent Psychiatry, 39*(4), 485–494. https://doi.org/10.1097/00004583-200004000-00018

Qi, J., Li, B.-Z., Zhang, Y., Pan, B., Gao, Y.-H., Zhan, H., Liu, Y., Shao, Y.-C., Weng, X.-C., & Zhang, X. (2021). Disrupted small-world networks are associated with decreased vigilant attention after total sleep deprivation. *Neuroscience, 471*, 51–60. https://doi.org/10.1016/j.neuroscience.2021.07.010

Qian, X., Loo, B. R. Y., Castellanos, F. X., Liu, S., Koh, H. L., Poh, X. W. W., Krishnan, R., Fung, D., Chee, M. W., Guan, C., Lee, T.-S., Lim, C. G., & Zhou, J. (2018). Brain-computer-interface-based intervention re-normalizes brain functional network topology in children with attention deficit/hyperactivity disorder. *Translational Psychiatry, 8*(1), Article 149. https://doi.org/10.1038/s41398-018-0213-8

Raza, M. Z., Omais, M., Arshad, H. M. E., Maqsood, Musab, & Nadeem, A. A. (2024). *Effectiveness of brain computer interface (BCI) based attention training game system for symptom reduction, behavioral enhancement, and brain function modulation in children with attention deficit* *hyperactivity disorder (ADHD): A systematic review*. OSF Registries. https://doi.org/10.17605/OSF.IO/85HPT

Rozas, C., Carvallo, C., Contreras, D., Carreño, M., Ugarte, G., Delgado, R., Zeise, M. L., & Morales, B. (2015). Methylphenidate amplifies long-term potentiation in rat hippocampus CA1 area involving the insertion of AMPA receptors by activation of β-adrenergic and D1/D5 receptors. *Neuropharmacology, 99*, 15–27. https://doi.org/10.1016/j.neuropharm.2015.07.003

Sebastián-Romagosa, M., Cho, W., Ortner, R., Sieghartsleitner, S., Von Oertzen, T. J., Kamada, K., Laureys, S., Allison, B. Z., & Guger, C. (2023). Brain–computer interface treatment for gait rehabilitation in stroke patients. *Frontiers in Neuroscience, 17*, Article 1256077. https://doi.org/10.3389/fnins.2023.1256077

Shaffer, D. (1983). A Children's Global Assessment Scale (CGAS). *Archives of General Psychiatry, 40*(11), Article 1228. https://doi.org/10.1001/archpsyc.1983.01790100074010

Sherman, E., Tan, J., & Hrabok, M. (2023). *A compendium of neuropsychological tests: Fundamentals of neuropsychological assessment and test reviews for clinical practice*. Oxford University Press.

Sidlauskaite, J., Sonuga-Barke, E., Roeyers, H., & Wiersema, J. R. (2016). Altered intrinsic organisation of brain networks implicated in attentional processes in adult attention-deficit/hyperactivity disorder: A resting-state study of attention, default mode and salience network connectivity. *European Archives of Psychiatry and Clinical Neuroscience, 266*(4), 349–357. https://doi.org/10.1007/s00406-015-0630-0

Slim, K., Nini, E., Forestier, D., Kwiatkowski, F., Panis, Y., & Chipponi, J. (2003). Methodological index for non-randomized studies (*MINORS*): Development and validation of a new instrument. *ANZ Journal of Surgery, 73*(9), 712–716. https://doi.org/10.1046/j.1445-2197.2003.02748.x

Sporns, O. (2011). The non-random brain: Efficiency, economy, and complex dynamics. *Frontiers in Computational Neuroscience, 5*, Article 5. https://doi.org/10.3389/fncom.2011.00005

Strahler Rivero, T., Herrera Nuñez, L. M., Uehara Pires, E., & Amodeo Bueno, O. F. (2015). ADHD rehabilitation through video gaming: A systematic review using PRISMA guidelines of the current findings and the associated risk of bias. *Frontiers in Psychiatry, 6*, Article 151. https://doi.org/10.3389/fpsyt.2015.00151

Sun, M. (2022). Study on antidepressant emotion regulation based on feedback analysis of music therapy with brain-computer interface. *Computational and Mathematical Methods in Medicine, 2022*(1), Article 7200678. https://doi.org/10.1155/2022/7200678

Teo, S.-H. J., Poh, X. W. W., Lee, T. S., Guan, C., Cheung, Y. B., Fung, D. S. S., Zhang, H. H., Chin, Z. Y., Wang, C. C., Sung, M., Goh, T. J., Weng, S. J., Tng, X. J. J., & Lim, C. G. (2021). Brain-computer interface based attention and social cognition training programme for children with ASD and co-occurring ADHD: A feasibility trial. *Research in Autism Spectrum Disorders, 89*, Article 101882. https://doi.org/10.1016/j.rasd.2021.101882

Tinius, T. P. (2003). The intermediate visual and auditory continuous performance test as a neuropsychological measure. *Archives of Clinical Neuropsychology, 12*(2), 199–214.

Trojan, S., & Pokorný, J. (1999). Theoretical aspects of neuroplasticity. *Physiological Research, 48*(2), 87–97.

Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world' networks. *Nature, 393*(6684), 440–442. https://doi.org/10.1038/30918

Xu, J., Yin, X., Ge, H., Han, Y., Pang, Z., Tang, Y., Liu, B., & Liu, S. (2015). Attentional performance is correlated with the local regional efficiency of intrinsic brain networks. *Frontiers in Behavioral Neuroscience, 9*, Article 200. https://doi.org/10.3389/fnbeh.2015.00200

Yan, N., Wang, J., Liu, M., Zong, L., Jiao, Y., Yue, J., Lv, Y., Yang, Q., Lan, H., & Liu, Z. (2008). Designing a brain-computer interface device for neurofeedback using virtual environments. *Journal of Medical and Biological Engineering, 28*(3), 167–172.

Zander, T. O., Kothe, C., Jatzev, S., & Gaertner, M. (2010). Enhancing human-computer interaction with input from active and passive brain-computer interfaces. In D. S. Tan & A. Nijholt (Eds.), *Brain-computer interfaces: Applying our minds to human-computer interaction* (pp. 181–199). Springer. https://doi.org/10.1007/978-1-84996-272-8_11

Received: August 24, 2024
Accepted: October 14, 2024
Published: March 24, 2025

Appendix A

Table 1A
Search Strategy of All Sources. (No Specific Search Strategy Was Used for ScienceDirect.)

Source	Search Strategy
PubMed	(“Attention Deficit Disorder with Hyperactivity”[Mesh] OR ADHD OR ADDH OR “Attention Deficit Disorders with Hyperactivity” OR “Attention Deficit Hyperactivity Disorders” OR “Attention Deficit Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorders” OR “Deficit-Hyperactivity Disorder, Attention” OR “Deficit-Hyperactivity Disorders, Attention” OR “Disorder, Attention Deficit-Hyperactivity” OR “Disorders, Attention Deficit-Hyperactivity” OR “Hyperkinetic Syndrome” OR “Syndromes, Hyperkinetic” OR “Attention Deficit Disorder” OR “Attention Deficit Disorders” OR “Deficit Disorder, Attention” OR “Deficit Disorders, Attention” OR “Disorder, Attention Deficit” OR “Disorders, Attention Deficit” OR “Brain Dysfunction, Minimal” OR “Dysfunction, Minimal Brain” OR “Minimal Brain Dysfunction”) AND (“Brain-Computer Interfaces”[Mesh] OR “Brain Computer Interfaces” OR “Interface, Brain-Computer” OR “Interfaces, Brain-Computer” OR “Brain-Computer Interface” OR “Brain Computer Interface” OR “Brain-Machine Interfaces” OR “Brain-Machine Interface” OR “Interface, Brain-Machine” OR “Interfaces, Brain-Machine” OR “Brain Machine Interface” OR “Brain Machine Interfaces” OR “Interface, Brain Machine” OR “Interfaces, Brain Machine” OR “Machine Interface, Brain” OR “Machine Interfaces, Brain” OR “attention training system” OR “attention training facility”)
Cochrane CENTRAL	(“Attention Deficit Disorder with Hyperactivity” OR ADHD OR ADDH OR “Attention Deficit Disorders with Hyperactivity” OR “Attention Deficit Hyperactivity Disorders” OR “Attention Deficit Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorders” OR “Deficit-Hyperactivity Disorder, Attention” OR “Deficit-Hyperactivity Disorders, Attention” OR “Disorder, Attention Deficit-Hyperactivity” OR “Disorders, Attention Deficit-Hyperactivity” OR “Hyperkinetic Syndrome” OR “Syndromes, Hyperkinetic” OR “Attention Deficit Disorder” OR “Attention Deficit Disorders” OR “Deficit Disorder, Attention” OR “Deficit Disorders, Attention” OR “Disorder, Attention Deficit” OR “Disorders, Attention Deficit” OR “Brain Dysfunction, Minimal” OR “Dysfunction, Minimal Brain” OR “Minimal Brain Dysfunction”) AND (“Brain-Computer Interfaces” OR “Brain Computer Interfaces” OR “Interface, Brain-Computer” OR “Interfaces, Brain-Computer” OR “Brain-Computer Interface” OR “Brain Computer Interface” OR “Brain-Machine Interfaces” OR “Brain-Machine Interface” OR “Interface, Brain-Machine” OR “Interfaces, Brain-Machine” OR “Brain Machine Interface” OR “Brain Machine Interfaces” OR “Interface, Brain Machine” OR “Interfaces, Brain Machine” OR “Machine Interface, Brain” OR “Machine Interfaces, Brain” OR “attention training system” OR “attention training facility”)
IEEE Xplore	(“Attention Deficit Disorder with Hyperactivity” OR ADHD OR ADDH OR “Attention Deficit Disorders with Hyperactivity” OR “Attention Deficit Hyperactivity Disorders” OR “Attention Deficit Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorders” OR “Deficit-Hyperactivity Disorder, Attention” OR “Deficit-Hyperactivity Disorders, Attention” OR “Disorder, Attention Deficit-Hyperactivity” OR “Disorders, Attention Deficit-Hyperactivity” OR “Hyperkinetic Syndrome” OR “Syndromes, Hyperkinetic” OR “Attention Deficit Disorder” OR “Attention Deficit Disorders” OR “Deficit Disorder, Attention” OR “Deficit Disorders, Attention” OR “Disorder, Attention Deficit” OR “Disorders, Attention Deficit” OR “Brain Dysfunction, Minimal” OR “Dysfunction, Minimal Brain” OR “Minimal Brain Dysfunction”) AND (“Brain-Computer Interfaces” OR “Brain Computer Interfaces” OR “Interface, Brain-Computer” OR “Interfaces, Brain-Computer” OR “Brain-Computer Interface” OR “Brain Computer Interface” OR “Brain-Machine Interfaces” OR “Brain-Machine Interface” OR “Interface, Brain-Machine” OR “Interfaces, Brain-Machine” OR “Brain Machine Interface” OR “Brain Machine Interfaces” OR “Interface, Brain Machine” OR “Interfaces, Brain Machine” OR “Machine Interface, Brain” OR “Machine Interfaces, Brain” OR “attention training system” OR “attention training facility”)

Table 1A

Search Strategy of All Sources. (No Specific Search Strategy Was Used for ScienceDirect.)

Source	Search Strategy
ClinicalTrials.gov	Condition or Disease: “Attention Deficit Disorder with Hyperactivity” OR ADHD OR ADDH OR “Attention Deficit Disorders with Hyperactivity” OR “Attention Deficit Hyperactivity Disorders” OR “Attention Deficit Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorders” OR “Deficit-Hyperactivity Disorder, Attention” OR “Deficit-Hyperactivity Disorders, Attention” OR “Disorder, Attention Deficit-Hyperactivity” OR “Disorders, Attention Deficit-Hyperactivity” OR “Hyperkinetic Syndrome” OR “Syndromes, Hyperkinetic” OR “Attention Deficit Disorder” OR “Attention Deficit Disorders” OR “Deficit Disorder, Attention” OR “Deficit Disorders, Attention” OR “Disorder, Attention Deficit” OR “Disorders, Attention Deficit” OR “Brain Dysfunction, Minimal” OR “Dysfunction, Minimal Brain” OR “Minimal Brain Dysfunction” Intervention or Treatment: “Brain-Computer Interfaces” OR “Brain Computer Interfaces” OR “Interface, Brain-Computer” OR “Interfaces, Brain-Computer” OR “Brain-Computer Interface” OR “Brain Computer Interface” OR “Brain-Machine Interfaces” OR “Brain-Machine Interface” OR “Interface, Brain-Machine” OR “Interfaces, Brain-Machine” OR “Brain Machine Interface” OR “Brain Machine Interfaces” OR “Interface, Brain Machine” OR “Interfaces, Brain Machine” OR “Machine Interface, Brain” OR “Machine Interfaces, Brain” OR “attention training system” OR “attention training facility”
WHO ICTRP	Condition: “Attention Deficit Disorder with Hyperactivity” OR ADHD OR ADDH OR “Attention Deficit Disorders with Hyperactivity” OR “Attention Deficit Hyperactivity Disorders” OR “Attention Deficit Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorder” OR “Attention Deficit-Hyperactivity Disorders” OR “Deficit-Hyperactivity Disorder, Attention” OR “Deficit-Hyperactivity Disorders, Attention” OR “Disorder, Attention Deficit-Hyperactivity” OR “Disorders, Attention Deficit-Hyperactivity” OR “Hyperkinetic Syndrome” OR “Syndromes, Hyperkinetic” OR “Attention Deficit Disorder” OR “Attention Deficit Disorders” OR “Deficit Disorder, Attention” OR “Deficit Disorders, Attention” OR “Disorder, Attention Deficit” OR “Disorders, Attention Deficit” OR “Brain Dysfunction, Minimal” OR “Dysfunction, Minimal Brain” OR “Minimal Brain Dysfunction” Intervention: “Brain-Computer Interfaces” OR “Brain Computer Interfaces” OR “Interface, Brain-Computer” OR “Interfaces, Brain-Computer” OR “Brain-Computer Interface” OR “Brain Computer Interface” OR “Brain-Machine Interfaces” OR “Brain-Machine Interface” OR “Interface, Brain-Machine” OR “Interfaces, Brain-Machine” OR “Brain Machine Interface” OR “Brain Machine Interfaces” OR “Interface, Brain Machine” OR “Interfaces, Brain Machine” OR “Machine Interface, Brain” OR “Machine Interfaces, Brain” OR “attention training system” OR “attention training facility”

Table 2A
Studies Excluded in Secondary Screening

Excluded Study	Reason for exclusion
Zhang 2021	Healthy participants only
Gonzales 2022	One healthy volunteer only
Ali 2015	Healthy participants only
Rohani 2014	Healthy participants only
Arpaia 2020	No gaming system
Pires 2011	Healthy participants only
Oliveira-Junior 2020	No gaming system and healthy participants only
Usman 2021	Healthy participants only
Khong 2014	Healthy participants only
Bach-Morrow 2022	No gaming system
Teo 2021	Participants taking concomitant medication
Sagiadinou 2020	BCI technology developed but not tested on subjects
Arvaneh 2019	Healthy participants only
Khan 2021	Healthy participants only
Reddy 2020	BCI technology developed but not tested on subjects

Table 3A
Characteristics of the Eleven Included Studies

Study ID	Study design	Type of diagnosed ADHD	Eligibility Criteria	Duration of training	Efficacy measures reported
Blandón et al. (2016)	Single-arm trial	N/A	Children clinically diagnosed with ADHD	Two sessions only	Time spent to complete the task and game-oriented tasks
Georgiou et al. (2019)	Single-arm trial		1) ADHD diagnosis and no previous treatment: participants should preferably have a new diagnosis according to the DSM IV-TR or DSM-5 during the previous 3 months before joining the study; 2) Additionally, participants should preferably not have taken any type of drug approved for the treatment of ADHD before starting the study; 3) Participants' age range will be between 8 and 15 years old, and will also depend on the age limitations of the AR equipment that will be used for the MMR game; 4) IQ range: participants must have an average IQ range; 5) No other deficits and disorders: participants will show no presence of neurological deficit, neurodevelopmental disorder, and will not have a comorbid diagnosis (e.g., autism spectrum disorder, depression, bipolar disorder)	-	Attention levels, theta-to-beta ratio (TBF)
Johnstone et al. (2017)	RCT (intervention-control)	Subclinical, inattentive and hyperactive type	1) Diagnosed based on DSM-IV criteria or scored in the borderline range on Conners 3-P scale; 2) No known history of epilepsy, periods of unconsciousness or serious head injuries; 3) No known psychological disorder; and 4) Have never displayed lower than expected academic abilities on WAIT-II scale	6-8 weeks	ADHD-RS scores (modified), CBCL (multiple)
Lim et al. (2010)	Control-matched single-arm trial	Inattentive and combined type	1) No previous pharmacological treatment; 2) No comorbid psychiatric condition/known sensorineural deficit; 3) No history of seizures; 4) No known mental retardation sign (IQ > 70)	10 weeks	ADHD-RS scores (both IA and HI)
Lim et al. (2012)	Single-arm trial	Inattentive and combined type	1) No previous pharmacological treatment; 2) Could satisfy DSM-IV-TR criteria; 3) No known sensorineural deficit or history of epilepsy; 4) IQ > 70	5 months (first 8 weeks one session per week, followed one session per month for 3 months)	ADHD-RS scores (both IA and HI)

Table 3A
Characteristics of the Eleven Included Studies

Study ID	Study design	Type of diagnosed ADHD	Eligibility Criteria	Duration of training	Efficacy measures reported
Lim et al. (2019)	RCT (intervention-control)	Inattentive and combined type	1) Diagnosed based on DSM-IV TR criteria; 2) Children previously receiving pharmacotherapy had to undergo a washout period of at least 4 weeks; 3) No known intellectual disability, epilepsy and severe sensorineural deficits or coexisting psychiatric disorder	5 months (first 8 weeks 1 session per week, followed 1 session per month for 3 months)	ADHD-RS scores (only IA), CGAS, CGI-S, and CBCL score (both internalizing and externalizing problems)
Lim et al. (2023)	RCT (Comparative)	Inattentive and combined type	1) Diagnosed by DSM-IV or DSM-5, inattentive or combined subtype; 2) no learning disability; 3) No previous pharmacological treatment (washout period of 1 month for meds, 3 months for supplements); 4) No psychiatric illness and IQ > 70	8 weeks	ADHD-RS scores (both IA and HI), CGAS, CGI-S, and CBCL score (attention, internalizing and externalizing, total and ADH problems),
Liu et al. (2013)	Single-arm trial	N/A	1) IQ > 80; 2) ADHD diagnosed by child psychiatrist; 3) Not taking concomitant stimulant medication; 4) No children with brain injury or comorbidity such as ASD and epilepsy	10 weeks	Scores of IVA-CTP
Park et al. (2019)	Single-arm trial	N/A	1) Diagnosed with ADHD, were receiving counselling at the time of the study	5 weeks	KNISE-BAAT score, general reading and comprehension questionnaires
Qian et al. (2018)	RCT (intervention-control)	Inattentive and combined type	1) Diagnosed based on DSM-IV criteria; 2) 1-month washout period for children previously on pharmacotherapy; 3) No known history of epilepsy and intellectual disability (IQ < 70)	8 weeks	ADHD-RS scores (only IA), CBCL (internalizing problems)
Yan et al. (2008)	Single-arm trial	N/A	Clinically diagnosed with ADHD	10 weeks	Scores of IVA-CTP

Table 4A

Inattention (IA), Hyperactive-Impulsivity (HI), and Modified Scores Reported in the Included Studies

Study ID	Assessor	ADHD-RS type	Time of assessment	Intervention group		Control group	
				Mean (SD)	Mean Difference (SD)	Mean (SD)	Mean Difference (SD)
Johnstone et al. (2017)	Parents	Modified total (score range of up to 72)	Baseline At week 8	40.6 (5.9) 28.6 (5.8)	N/A	40.6 (1.37) 38.1 (1.19)	N/A
	Teachers	Modified total (score range of up to 72)	Baseline At week 8	26.27 (4.08) 18.03 (3.89)	N/A	26.2 (0.54) 27.1 (0.54)	N/A
Lim et al. (2010)	Teachers	IA score	Baseline At week 5	16.6 (9.7) 14.0 (8.3)		12.3 (3.6) 13.2 (4.3)	
			At week 10	10.6 (9.0)	Baseline/week 10 = −6.0 (5.9)	11.5 (4.8)	Baseline/week 10 = −0.8 (5.6)
		HI score	Baseline At week 5 At week 10	16.8 (9.3) 14.6 (7.7) 11.2 (7.3)	Baseline/week 10 = −5.6 (2.2)	15.0 (6.1) 13.8 (6.4) 10.5 (4.8)	Baseline/week 10 = −4.5 (7.6)
	Parent	IA score	Baseline At week 5	18.0 (6.1) 17.8 (6.0)		17.9 (5.7) 18.4 (6.0)	
			At week 10	15.0 (5.9)	Baseline/week 10 = −3.0 (4.8)	18.6 (5.7)	Baseline/week 10 = 0.8 (1.3)
		HI score	Baseline At week 5	14.9 (5.6) 14.1 (5.7)		17.6 (5.0) 16.5 (5.1)	
			At week 10	11.4 (4.6)	Baseline/week 10 = −3.5 (4.5)	15.6 (5.7)	Baseline/week 10 = −1.0 (1.7)
Lim et al. (2012)	Parents	IA score	Baseline	17.7 (5.0)			
			At week 8	13.1 (5.0)	Baseline/week 8 = −4.6 (5.9, *P* = .003)		
			At week 20	13.6 (4.5)			
			At week 24	12.6 (3.4)	Baseline/week 24 = −5.0 (5.8, P < .01)		
		HI score	Baseline	15.6 (3.9)			
			At week 8	10.9 (4.4)	Baseline/week 8 = −4.7 (5.6, *P* = .002)		
			At week 20	10.2 (5.1)			
			At week 24	10.5 (4.3)	Baseline/week 24 = −5.7 (5.1, *P* < .01)		

Table 4A

Inattention (IA), Hyperactive-Impulsivity (HI), and Modified Scores Reported in the Included Studies

Study ID	Assessor	ADHD-RS type	Time of assessment	Intervention group		Control group	
				Mean (SD)	Mean Difference (SD)	Mean (SD)	Mean Difference (SD)
Lim et al. (2019)	Clinician	IA score	Baseline	18.9 (4.25)		18.6 (4.38)	
			At week 8	15.5 (4.48)	Baseline/ week 8 = −3.5 (3.87)	16.7 (5.14)	Baseline/ week 8 = 1.9 (4.42)
			At week 20	15.6 (5.26)	Baseline/ week 20 = −3.3 (5.55)		
			At week 24	15.6 (5.26)	Baseline/ week 24 = −4.7 (5.94)		
	Parents	IA score	Baseline	18.9 (4.84)		18.6 (4.24)	
			At week 8	N/A	Baseline/ week 8 = −4.0 (4.80)		Baseline/ week 8 = −1.8 (4.21)
			At week 20	N/A	Baseline/ week 20 = -4.1 (5.59)		
			At week 24	N/A	Baseline/ week 24 = -5.3 (6.17)		
Lim et al. (2023) [The intervention is clinic and the control is home]	Clinician	IA score	Baseline	16.1 (5.69)		17.9 (5.61)	
			At week 8	14.0 (6.30)	Baseline/week 8 = 3.9 (5.09)	14.7 (4.97)	Baseline/ week 8 = 3.2 (6.20)
		HI score	Baseline	10.9 (8.16)		12.5 (5.72)	
			At week 8	10.3 (5.02)	Baseline/week 8 = 2.5 (4.34)	11.2 (6.23)	Baseline/ week 8 = 1.3(4.17)
	Parents	IA score	Baseline	15.9 (6.97)		17.7 (4.32)	
			At week 8	14.1 (6.31)	Baseline/week 8 = 1.8 (4.39)	14.7 (4.97)	Baseline/ week 8 = 3.0 (4.24)
		HI score	Baseline	11.8 (8.44)		12.2 (5.37)	
			At week 8	9.7 (5.29)	Baseline/week 8 = 2.1 (4.15)	11.4 (6.26)	Baseline/ week 8 = 0.8 (3.74)
Qian et al. (2018)	Parents	IA score	Baseline	16.27 (4.25)		18.9 (5.18)	
			At week 8	13.16 (4.07)		17.2 (5.76)	

Table 5A

Pre- and Postinterventional RCQ and AQ Scores Reported by Two Studies

Study ID	Time point	RCQ						AQ					
		Overall		Auditory		Visual		Overall		Auditory		Visual	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Yan et al. (2008)	Pretreatment	84.29	14.291	85.143	15.082	87.143	19.777	71.143	15.279	79.286	16.799	68.857	19.786
	Posttreatment	95.857	9.685	97.286	10.095	94.571	13.636	93.429	12.012	96.572	16.257	90.857	11.098
Liu et al. (2013)	Pretreatment	83.216	16.172	86.357	17.372	83.929	17.394	70.572	16.928	74.571	18.364	72.143	21.746
	Posttreatment	97.286	6.900	98.571	7.208	96.714	10.179	94.071	8.325	91.857	9.114	95.143	11.408

Table 6A

Assessment of Risk of Bias of Nonrandomized Studies Using MINORS. Each Criterion Can Receive a Score of 0, 1, or 2. N/A Shows That the Criterion Was Not Applicable to That Study Because It Was Noncomparative.

Study	General Criteria								Specific Criteria for Comparative Studies				Overall
	Aim	Consecutive Patients	Prospective Data Collection	Appropriate Endpoints	Unbiased Assessment	Appropriate Follow-up	Loss to Follow-up	Study Size Calculation	Adequate Control Group	Contemporary Groups	Baseline Equivalence	Adequate Statistics	
Lim et al. (2010)	**2**	**2**	**2**	**2**	**1**	**2**	**0**	**2**	**1**	**2**	**1**	**2**	**19**
Lim et al. (2012)	**2**	**2**	**2**	**2**	**0**	**2**	**2**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**12**
Blandón et al. (2016)	**2**	**0**	**2**	**1**	**0**	**0**	**2**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**7**
Park et al. (2019)	**2**	**2**	**2**	**1**	**0**	**2**	**2**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**11**
Georgiou et al. (2019)	**2**	**1**	**2**	**2**	**0**	**2**	**1**	**1**	**N/A**	**N/A**	**N/A**	**N/A**	**11**
Yan et al. (2008)	**2**	**1**	**2**	**2**	**0**	**2**	**2**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**11**
Liu et al. (2013)	**2**	**0**	**2**	**1**	**0**	**2**	**0**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**7**

NeuroRegulation

Effectiveness of HRV Biofeedback in Decreasing Anger Among Adolescents With Autism Spectrum Disorder

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Abstract

This study investigates the use of heart rate variability (HRV) biofeedback to manage anger in autistic adolescents. Anger, a natural but potentially maladaptive response to stress, is particularly prevalent among adolescents and is compounded for those on the autism spectrum due to difficulties with sensory processing and communication. Previous research suggests that biofeedback is a promising tool for managing anger. This study examines the effects of HRV biofeedback, both alone and in combination with de-escalation techniques, on reducing anger frequency and intensity among three autistic adolescents. Results show a significant decrease in both anger episodes and intensity during the HRV biofeedback condition, with further reductions observed when de-escalation strategies were added. These improvements were maintained during a 6-month follow-up, indicating the potential for long-term benefits. The study suggests that HRV biofeedback, especially when paired with cognitive-behavioral strategies, may offer an effective, noninvasive, and sustainable approach to anger management for autistic adolescents.

Keywords: anger; autism; adolescence; biofeedback; HRV

Citation: Hillman, H. (2025). Effectiveness of HRV biofeedback in decreasing anger among adolescents with autism spectrum disorder. *NeuroRegulation, 12*(1), 79–85. https://doi.org/10.15540/nr.12.1.79

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Anger is a natural human emotion that serves as an adaptive response to perceived threats (Fessler, 2010). While anger can motivate individuals to act, its expression often conflicts with societal norms that discourage displays of anger (Dearing et al., 2002). Chronically suppressed anger can become maladaptive when it culminates in aggressive outbursts, violent behavior, or destructive acts (Levey & Howells, 1990; Maiuro et al., 1988). Given the potential social, psychological, and physical consequences of poorly managed anger, it is crucial to understand and address anger as a distinct behavioral concern.

Adolescence is a developmental stage when anger may become particularly pronounced due to the concurrent physical, cognitive, and social changes that characterize this life phase (Wilde, 1995). As adolescents navigate the challenges of increased autonomy, hormonal fluctuations, and shifting parent-child relationships, some may struggle with intensified negative emotions and anger (Steinberg & Morris, 2001). Within the adolescent population, those on the autism spectrum may face unique challenges in managing anger. Challenges with sensory integration and communication can contribute to more frequent or intense anger experiences among autistic youth compared to their neurotypical peers (Quetsch et al., 2023). For example, Quetsch et al. (2023) found that upwards of 50% of autistic adolescents exhibited aggressive behaviors often linked to anger dysregulation. Another study discovered that autistic adolescents self-reported higher levels of repetitive dwelling on angry thoughts (Patel et al., 2016). Therefore, it is essential to develop targeted interventions that address the specific anger management needs of autistic adolescents.

Existing treatments for adolescent anger often encompass medication and treatments that rely on identifying antecedents to anger episodes—such as de-escalation techniques, anger episode recognition skills, and social support. However, many adolescents prone to anger outbursts frequently struggle to identify the precursors to their anger escalation (Mostofsky et al., 2013). Biofeedback training may offer a promising adjunctive therapy for teaching adolescents to recognize anger antecedents. Biofeedback involves using equipment to provide individuals with real-time physiological feedback aimed at increasing self-awareness and promoting voluntary control over bodily responses for improved health and performance (e.g., Lehrer et al., 2000; Lin et al., 2023). Over the years, research has demonstrated biofeedback's efficacy across over 40 health conditions, including anxiety, ADHD, headaches, insomnia, and chronic pain (Frank et al., 2010).

Autistic adolescents with frequent anger episodes may particularly benefit from learning to use biofeedback to identify their anger triggers. One potential physiological marker of anger arousal is heart rate variability (HRV), which reflects the body's stress response. HRV biofeedback involves teaching individuals to modify their breathing patterns to influence HRV and promote relaxation, similar to the principles of mindfulness meditation (Ratajczak et al., 2021). While several studies have explored the use of biofeedback for emotional regulation in adolescents, none have specifically evaluated HRV biofeedback for anger management in autistic adolescents. One study with adults found that short-term HRV biofeedback increased HRV and reduced anger, suggesting that HRV may be an index of anger regulation (Francis et al., 2015). However, the long-term anger management benefits of HRV biofeedback remain unknown and warrant further investigation.

The increasing availability of affordable and user-friendly biofeedback devices that track HRV presents opportunities to make this intervention more accessible. However, the literature lacks studies examining the application of HRV biofeedback for anger management in autistic adolescents. The current study aims to address this gap by evaluating the effectiveness of HRV biofeedback in reducing anger episodes among three autistic adolescents. By acknowledging the unique experiences of autistic individuals and implementing tailored support strategies, we can enhance the anger management skills and resilience of this population.

A Note About Semantics

Identity-first language such as “autistic individuals” rather than person-centered language is used in this article. When communicating about disabilities, it is important to consider how those with the disability refer to themselves, as semantics is significant. Many individuals in the autism community prefer identity-first language because we view autism as a central and inseparable part of our identity (Ryan, 2019).

Methods

Participants

Participants were three adolescents who wanted to learn how to manage their anger, recruited from a mental health clinic that provided counseling services. All participants had (a) an autism spectrum disorder (ASD) diagnosis, (b) a demonstrated history of anger-related behaviors (e.g., yelling, losing temper, arguing) that interfered with daily functioning, and (c) were willing to visit the clinic weekly. A university Internal Review Board (IRB) from the respective university approved the study; participant and parental consent were obtained prior to starting, and participants were assigned an identification number to maintain confidentiality.

Participant 1, an only child, was a 16-year-old male diagnosed with ASD at 6 years of age. He reported challenges controlling his sporadic, daily anger outbursts, which he described as explosive. At the time of the study, he was in the 11th grade and lived with his father.

Participant 2, an 18-year-old male and the youngest of two children, was diagnosed with ASD at the age of 5. He reported experiencing anger episodes daily, and it negatively interfered with him forming and maintaining relationships with others. Participant 2 reported the smallest annoyances would make him angry, and his anger consisted of swearing and yelling. At the time of the study, he was in the 12th grade and lived at home with his parents and siblings.

Participant 3, a 13-year-old male diagnosed with ASD at the age of 4, was in the 7th grade and lived with his mother and twin sibling. Participant 3’s mother reported him exhibiting anger outbursts and yelling at both her and his brother numerous times daily with little warning. Participant 3 reported he liked to tell others what to do and became angry when he did not get his way. At home he physically pushed others, yelled at his mom and brother, and slammed doors. At school he was suspended four times for pushing and swearing at students and teachers.

Setting and Measures

All biofeedback sessions were conducted in a private office at a counseling clinic. A HeartMath emWave2 portable unit was used during the study to measure HRV through an electrode attached to an ear using an ear clip.

Design and Procedure

The study used multiple baseline across participants, consisting of baseline, HRV biofeedback condition, HRV biofeedback plus de-escalation techniques condition, and a 6-month follow-up. After baseline, participants completed 15-min HRV biofeedback sessions twice weekly across 4 weeks, followed by 15-min HRV biofeedback sessions along with 10 min of practicing de-escalation techniques twice weekly across 4 weeks, followed by monthly follow-up probes for 6 months.

During baseline, participants recorded the number of daily anger episodes and the intensity of each episode on a recording form (see Figure 1); no interventions were implemented. Prior to starting the HRV biofeedback condition, participants were shown how to use the emWave2 unit—to change the light from red to green—and practiced breathing while connected to the emWave2 unit.

During the HRV biofeedback condition, participants completed a 15-min HRV session, twice a week across 4 weeks, in a private clinic room. For each session, the researcher assisted participants with connecting to the emWave2 unit, then left the room while participants independently completed the HRV session. During the HRV biofeedback plus de-escalation condition, participants completed a HRV session followed by practicing de-escalation techniques with the researcher. During the first HRV plus de-escalation techniques session, participants were taught a four-step de-escalation strategy to use daily whenever they began feeling angry. The four steps were to (1) breathe in slowly for four counts and exhale for four counts, (2) say "I am feeling angry at the moment, and that is okay," (3) imagine being at your happy place (e.g., skateboarding with a friend, with your dog, at home), and (4) slowly walk away from the situation to another place (e.g., around the school, outside, for a walk or skateboarding).

During the follow-up phase, participants were provided with an emWave2 unit for home use, allowing them to use it at their own discretion rather than following a prescribed frequency. They were instructed to record episodes of anger and their associated intensity using the designated tracking form, as well as to note the frequency of emWave2 usage each week. At the start of each month, participants met with the researcher to submit their completed forms for review.

Figure 1. *Participant Daily Monitoring Form.*

Participant Daily Monitoring Form
ID Number:______________________________ Today's Date: ______________________
Directions: Find correct time and circle the intensity of your emotion

(1-5, with 1 being calm and 5 being really angry).
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
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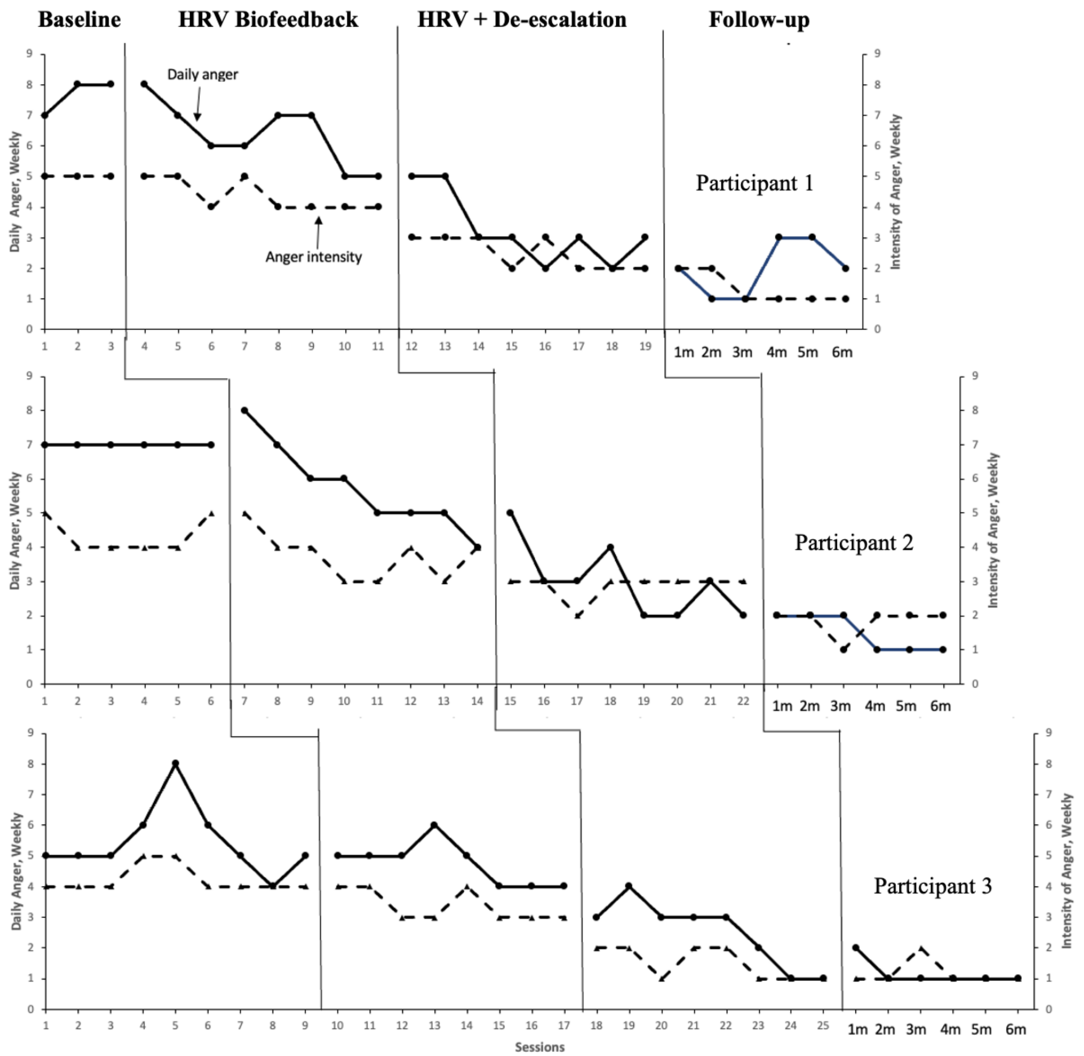
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5
Time of anger episode: __________________ Rating of your emotion: 1 2 3 4 5

Results

All participants experienced a decrease in anger episodes during the HRV biofeedback condition. A de-escalation component was added to the HRV biofeedback to evaluate whether participants' anger would reduce further. All participants experienced a further decrease in anger episodes during the HRV biofeedback plus de-escalation condition (see Figure 2). During the HRV biofeedback condition, Participant 1 experienced an average of 6.3 anger episodes per day, a decrease from an average of 7.6 daily anger episodes during baseline. His anger episodes further decreased to an average of 3.2 anger episodes daily after the HRV biofeedback plus de-escalation condition was implemented.

Figure 2. *Weekly Anger Episodes (Left Y Axis) and Anger Intensity (Right Y Axis) Across Participants.*



Participant 2 experienced an average of 5.7 anger episodes per day during the HRV biofeedback condition, a decrease from seven daily anger episodes during baseline. His anger episodes decreased further to an average of three daily episodes during the HRV biofeedback plus de-escalation condition.

Participant 3 experienced an average of 4.7 daily anger episodes during the HRV biofeedback condition, a slight decrease from baseline level of 5.4 daily anger episodes. His anger episodes decreased even further, to an average of 2.5 daily angry episodes, during the HRV biofeedback plus de-escalation condition. Anger episodes for all participants decreased further and maintained at low rates during the follow-up condition.

As the number of anger episodes decreased, so did the intensity of the participants' anger (see Figure 2). Participant 1 reported his anger intensity, during baseline, was a 5 (mode = 5). He reported the intensity of his anger decreased to 4 (mode = 4) by the end of the HRV biofeedback condition and decreasing further to 2.5 (mode = 3) by the end of the HRV biofeedback plus de-escalation condition.

Participant 2 reported the intensity of his anger during baseline was 4 (mode = 4). His reported anger intensity decreased to 3.75 (mode = 4) during the HRV biofeedback and decreased further to 2.8 (mode = 3) during the HRV biofeedback plus de-escalation condition.

Participant 3 reported his anger intensity during baseline was 4.5 (mode = 4) and decreasing to 3 (mode = 3) by the end of the HRV biofeedback condition and decreasing further to a 1.5 (mode split between 1 and 2) during the HRV biofeedback plus de-escalation condition.

All participants reported their anger intensity remained at or below the levels observed during the intervention phase during the follow-up period. Furthermore, Participant 1 and Participant 2 reported using the emWave2 device once per week, while Participant 3 reported using the device twice per week during the follow-up phase.

Discussion

The study demonstrated the effectiveness of HRV biofeedback, both alone and in conjunction with de-escalation techniques, in reducing anger episodes among autistic adolescents. Even though participants' anger episodes decreased during the HRV biofeedback condition, the researcher wanted to examine whether an addition of de-escalation techniques that participants used between biofeedback sessions would help further decrease the number of anger episodes. All participants exhibited a significant decrease in both the frequency and intensity of anger episodes, that sustained during the follow-up probes. The results suggest that HRV biofeedback, particularly when paired with de-escalation strategies, could be a valuable tool in managing anger among this population.

One reason for the decreased intensity of anger among participants may be related to the roles of the amygdala and cortisol in the anger response. The amygdala triggers the initial anger response, leading to increased cortisol levels that help manage stress. Cortisol levels peak shortly after anger onset and generally return to baseline within a few hours. If anger occurs again before cortisol levels normalize, the heightened state of arousal and increased sensitivity can lead to more intense anger episodes, since high cortisol amplifies perceptions of threats and makes emotional regulation more difficult, contributing to sustained anger. As participants experienced fewer anger episodes, it is likely their cortisol levels were lower, reducing their sensitivity to triggers that previously caused more intense anger episodes.

The current study adds to the biofeedback literature by (a) evaluating the effectiveness of HRV biofeedback on anger regulation among adolescents, (b) comparing the effectiveness of HRV biofeedback with and without de-escalation techniques, and (c) collecting follow-up data, which is limited in the HRV biofeedback literature.

Strengths

One of the strengths of this study was its focus on personalization and feasibility. The study was implemented in a real-world setting, utilizing a portable HRV device that participants operated independently, demonstrating the practicality of the intervention. This approach not only made the intervention more accessible but also demonstrated its practicality, allowing participants to integrate the practice into their daily lives.

A second strength was the sustained impact observed during the follow-up probes. Unlike many biofeedback studies that did not collect follow-up data after the completion of the intervention (Hillman & Chapman, 2018) this study collected data after the intervention ended, showing a maintained reduction in anger episodes. Collecting data after the completion of the intervention is as important as collecting data during intervention implementation. The consistent reduction in anger episodes even after the intervention ended suggests that the benefits of HRV biofeedback, particularly when combined with de-escalation techniques, sustains beyond the immediate treatment phase. This highlights the potential for long-term effectiveness, offering a lasting solution for helping autistic adolescents manage their anger.

Lastly, the study's multifaceted approach is noteworthy. By integrating HRV biofeedback with de-escalation techniques, the intervention addressed both the physiological and cognitive components of anger management. This comprehensive strategy likely contributed to the overall success of the intervention, as it not only helped participants regulate their physiological responses but also equipped them with practical skills to manage their anger in real-world situations.

Limitations

Even though the study has multiple strengths, it does have areas where future research could improve upon. One of the limitations of this study was the short follow-up condition. Even though the current study included 6 months of follow-up data, future studies should collect longer follow-up data. More research collecting follow-up data on the effectiveness of HRV biofeedback on anger management is needed to demonstrate not just the effectiveness of biofeedback but also the duration of the treatment gains.

Second, since anger does not occur in one setting, success of a biofeedback intervention should be judged based on the ability of participants managing their anger in multiple settings. Unfortunately, the current study did not evaluate generalizability of the biofeedback intervention. More research collecting generalization data is needed to close the gap that exists between demonstrating HRV biofeedback effectively reduces anger in one setting and demonstrating the generalization of HRV biofeedback across multiple settings.

A third limitation of this study was the small sample size of only three participants. This raises concerns about the generalizability of the findings to the broader population of autistic adolescents. While the results are promising, they cannot be confidently extended to a larger group without further research. Future studies utilizing biofeedback for anger management in autistic adolescents should aim to include larger sample sizes, allowing for a more comprehensive understanding of the intervention's efficacy and ensure that the results are representative of a more diverse population.

Fourth, the study's reliance on self-reported measures for anger intensity introduces the possibility of bias. Participants may unintentionally overreport or underreport their anger levels due to subjective interpretations or the desire to present themselves in a favorable light. This could skew the data and impact the accuracy of the findings. Incorporating more objective measures of anger intensity, such as observational assessments or third-party reports, could help mitigate this bias and provide a more accurate reflection of the intervention's impact.

Conclusion

While more evidence is needed to support the effectiveness of HRV biofeedback on anger management among autistic adolescents, the preliminary data gathered in this study suggests that HRV biofeedback plus de-escalation is a promising tool autistic adolescents can use to manage their anger. Continued research on the effects of biofeedback on anger among autistic adolescents is highly recommended since it is less invasive, does not involve medications, and is potentially less expensive and more effective than other counseling or anger management alternatives (Frank et al., 2010; Nordqvist, 2017). With both the frequency and intensity of anger among adolescents on the rise in today's society and given there is little published research in the area, further research studying the effectiveness of biofeedback on anger management of adolescents not only seems necessary but is also strongly encouraged.

Author Disclosure

The author has no grant support, financial interest, or conflicts to disclose.

References

Dearing, K. F., Hubbard, J. A., Ramsden, S. R., Parker, E. H., Relyea, N., Smithmyer, C. M., & Flanagan, K. D. (2002). Children's self-reports about anger regulation: Direct and indirect links to social preference and aggression. *Merrill-Palmer Quarterly, 48*(3), 308–336. https://doi.org/10.1353/mpq.2002.0011

Fessler, D. M. T. (2010). Madmen: An evolutionary perspective on anger and men's violent responses to transgression. In M. Potegal, G. Stemmler, & C. Spielberger (Eds.), *International handbook of anger: Constituent and concomitant biological, psychological, and social processes* (pp. 361–381). Berlin, German: Springer Science and Business Media. https://doi.org/10.1007/978-0-387-89676-2_21

Francis, H. M., Penglis, K. M., & McDonald, S. (2015). Manipulation of heart rate variability can modify response to anger-inducing stimuli. *Social Neuroscience, 11*(5), 545–552. https://doi.org/10.1080/17470919.2015.1115777

Frank, D. L., Khorshid, L., Kiffer, J. F., Moravec, C. S., & McKee, M. G. (2010). Biofeedback in medicine: Who, when, why and how? *Mental Health in Family Medicine, 7*(2), 85–91.

Hillman, H., & Chapman, C. J. (2018). Biofeedback and anger management: A literature review. *NeuroRegulation, 5(1),* 43–49. https://doi.org/10.15540/nr.5.1.43

Lehrer, P. M., Vaschillo, E., & Vaschillo, B. (2000). Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training. *Applied Psychophysiology Biofeedback, 25,* 177–191. https://doi.org/10.1023/a:1009554825745

Levey, S., & Howells, K. (1990). Anger and its management. *The Journal of Forensic Psychiatry, 1*(3), 305–327. https://doi.org/10.1080/09585189008408480

Lin, I.-M., Chen, T.-C., Tsai, H.-Y., & Fan, S.-Y. (2023). Four sessions of combining wearable devices and heart rate variability (HRV) biofeedback are needed to increase HRV indices and decrease breathing rates. *Applied Psychophysiology Biofeedback, 48*, 83–95. https://doi.org/10.1007/s10484-022-09567-x

Maiuro, R. D., Cahn, T. S., Vitaliano, P. P., Wagner, B. C., & Zegree, J. B. (1988). Anger, hostility, and depression in domestically violent versus generally assaultive men and nonviolent control subjects. *Journal of Consulting and Clinical Psychology, 56*(1), 17–23. https://doi.org/10.1037/0022-006X.56.1.17

Mostofsky, E., Maclure, M., Tofler, G. H., Muller, J. E., & Mittleman, M. A. (2013). Relation of outbursts of anger and risk of acute myocardial infarction. *The American Journal of Cardiology, 112*(3), 343–348. https://doi.org/10.1016/j.amjcard.2013.03.035

Nordqvist, J. (2017). *What is biofeedback therapy and who can benefit*? Medical News Today. https://www.medicalnewstoday.com/articles/265802.php

Patel, S., Day, T. N., Jones, N., & Mazefsky, C. A. (2017). Association between anger rumination and autism symptom severity, depression symptoms, aggression, and general dysregulation in adolescents with autism spectrum disorder. *Autism, 21*(2), 181–189. https://doi.org/10.1177/1362361316633566

Quetsch, L. B., Brown, C., Onovbiona, H., Bradley, R., Aloia, L., & Kanne, S. (2023). Understanding aggression in autism across childhood: Comparison with a non-autistic sample. *Autism Research, 16*(6), 1185–1198. https://doi.org/10.1002/aur.2930

Ratajczak, E., Hajnowski, M., Stawicki, M., & Duch, W. (2021). Novel methodological tools for behavioral interventions: The case of HRV-biofeedback. Sham control and quantitative physiology-based assessment of training quality and fidelity. *Sensors, 21(11),* Article 3670. https://doi.org/10.3390%2Fs21113670

Ryan, M. (2019). *I proudly call myself autistic: Here is why*. SBS. Retrieved June 9, 2024. https://www.sbs.com.au/voices/article/i-proudly-call-myself-autistic-heres-why/hgi7yl6zz

Steinberg, L., & Morris, A. S. (2001). Adolescent development. *Annual Review of Psychology, 52*, 83–110. https://doi.org/10.1146/annurev.psych.52.1.83

Wilde, J. (1995). *Treating anger, anxiety, and depression in children and adolescents: A cognitive-behavioral perspective*. Taylor & Francis. https://doi.org/10.4324/9780203768051

Received: November 11, 2024
Accepted: December 18, 2024
Published: March 24, 2025