Portable EEG neurofeedback training applied at home or school to treat children's symptoms of ADHD

Julia Johanna Jörgens, s2092751
Faculty of Behavioural Science, Psychology
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1st Supervisor: Dr. Gert-Jan Prosman
2nd Supervisor: Dr. Matthijs Noordzij

Abstract

Introduction: ADHD is one of the most prevalent psychological childhood disorders. Still, effective treatment methods like stimulant medication or cognitive behaviour therapy have limitations regarding medication-related side effects and long waiting times before treatment provision. Portable EEG neurofeedback treatment, hence treatment applied in a non-clinical setting like schools and at home, might be a timely non-pharmacological alternative treatment option. Still, whereas EEG neurofeedback treatment applied in a clinical context has been researched for some decades already with promising findings of effectiveness, less is known about the effect of portable EEG neurofeedback in ADHD treatment. Therefore, to employ portable EEG neurofeedback interventions in treatment for ADHD, more insight is needed to the current research status of this treatment method for ADHD.

Methods: A scoping review was performed, searching three databases, namely PsycInfo, Scopus, and Web of Science. A total of eight studies were reviewed, tabulated and analysed to explore present evidence of portable EEG neurofeedback to treat ADHD, devices and software used during treatment, and measurement tools used to monitor symptoms of ADHD.

Results: Portable EEG neurofeedback interventions were conducted most often in a home setting in reviewed studies (n = 5). The technologies used were different portable EEG devices consisting of one active electrode within a headband and multiple active electrodes embedded in a cap. To monitor symptoms of ADHD, the majority of reviewed studies used third-party assessments of teachers and parents. One study used EEG devices' internal data to measure attention level changes. Neurofeedback treatment at school showed higher effects on ADHD symptomatology than at-home treatment. Whereas most studies present weak to moderate effect sizes, some studies present significant reductions in ADHD symptoms after portable EEG neurofeedback treatment.

Discussion: This scoping review shows that there is only little evidence present in the literature regarding the effectiveness of portable EEG neurofeedback. Hence, future research on this topic is needed. Here, the focus should be on the effects of individualised EEG neurofeedback treatment, with the use of EEG device internal assessments of ADHD symptomatology, as well as the inclusion of follow-up measures to account for probable long-term effects.

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Attention deficit hyperactivity disorder (ADHD) is one of the most prevalent psychological childhood disorders. It is estimated that five per cent of school-age and pre-school children worldwide are diagnosed with this mental health disease (Egger et al., 2006). Approximately half of those children will carry symptoms into adulthood (Kessler et al., 2006). Clinical guidelines recommend a multimodal treatment approach for ADHD treatment. Here, stimulant medication and cognitive behaviour therapy are most widely used and successful, with high effect sizes (AWMF, 2017; National Institute for Health and Care Excellence, 2018; Michelson et al., 2002). Still, both treatment modalities have limitations. Pharmacological benefits are limited in various situations due to poor adherence, side effects and negative medication-related attitudes from caregivers (Banaschewski et al., 2006). Further, limited long-term effects of stimulant medication have been reported (e.g. Wang et al., 2013). Additionally, access to cognitive behaviour therapy is often not provided in a timely manner. In 2019, the German federal chamber of psychotherapists evaluated approximately 300.000 insured persons' data. They found that among those patients needing psychotherapeutic treatment based on psychological consultation sessions, around 40 per cent waited at least three to nine months for the treatment to start. Hence, almost half of the mentally ill people waited unacceptably long for necessary treatment (Bundes Psychotherapeuten Kammer, 2021).

Based on these shortcomings, an alternative, more easily accessible non-pharmacological treatment option for ADHD is needed. Such a treatment option might be portable electroencephalography (EEG) neurofeedback treatment for use in non-clinical settings like home or school. However, even though EEG neurofeedback seems to be effective in treating ADHD (Arns et al., 2020) and its portable use would increase access to treatment of ADHD, no outline of the current state of research on this treatment method is present in literature. Hence, this thesis is going to conceptualise the scope of present research regarding portable EEG neurofeedback treatment applied at home or in school to treat children diagnosed with ADHD.

Attention deficit hyperactivity disorder

ADHD is primarily diagnosed by referring to diagnostic criteria of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) or the International Statistical Classification of Mental Disorders (ICD-10). According to the DSM-5, the main features of ADHD are persistent patterns of inattention, hyperactivity and impulsivity (American Psychiatric Association, 2013). Inattentive behaviour is conceptualised as a lack of attention in social, occupational and school contexts. Hence, careless mistakes, not listening when spoken to directly, being easily distractible or having difficulties organising relates to inattentive behaviour. Hyperactive behaviour relates to excessive fidgetiness like not sitting still or remaining seated when asked, excessive running, or talking excessively. Finally, reacting to situations without considering consequences is conceptualised as impulsive behaviour. Hence, impatience, interrupting others while speaking, or desire for immediate rewards are characteristic impulsive behaviours (American Psychiatric Association, 2013). Additionally, it is known that children diagnosed with ADHD show deficits in executive and cognitive function, i.e. planning and problem solving (Davey, 2014). As shown by magnetic resonance imagining (MRI) studies (e.g. Krain & Castellanos, 2006), abnormalities in specific brain regions controlling executive functioning may be responsible.

A comprehensive assessment is needed to diagnose and monitor ADHD symptoms. Therefore, information from several contexts like parents, teachers or other relevant adults close to the child is required for a good assessment (Rohde et al., 2019). The Dutch federation of medical specialists recommends conducting semi-structured interviews to diagnose ADHD. Commonly used semi-structured interviews are the Parent Interview for Child symptoms (PICS) and the Teacher Telephone interview (TTI), which show good reliability and validity measures (Ickowicz et al., 2006). In addition, the ADHD rating scale (ADHD-RS) is regularly used in practice to monitor symptoms. Nevertheless, questionnaires monitoring the symptom level of ADHD have been little researched. Therefore, there is limited evidence of whether these questionnaires are responsive (Federatie Medisch Specialisten, 2018). Next to external sources assessing ADHD symptoms of children, Rhode et al. (2019) point out that including the child's own perspective of symptoms in the assessment process is essential.

EEG neurofeedback

EEG neurofeedback is a form of biofeedback that assist subjects in monitoring and altering their brain waves in response to transferred and visualised brain states. When cerebral neurons are active, electrical impulses are produced (Rogers et al., 2016). These impulses can be recorded with an electroencephalogram (EEG) by placing electrodes on the scalp. Electrical impulses are quantified to electrical patterns known as brain waves that are distinguishable by their frequencies and amplitudes. The frequency of a brain wave is measured by the number of waves per second (Hz), which indicates how fast a wave oscillates. The brain wave's amplitude represents its power, measured by microvolt (μV) (Marzbani et al., 2016; Sterman, 2000). It can be distinguished between four brain waves, based on frequencies and amplitudes, that are of particular interest in characterising brain function and associated with different physiological and behavioural functions. These waves are delta (less than 4 Hz), theta (4 – 8 Hz), alpha (8 – 12 Hz), beta (15 – 27 Hz), and gamma (30 – 100 Hz). Further, there are subsets of these brain waves, like the sensorimotor rhythm (SMR) (12 – 15 Hz) or low beta (15 – 19 Hz) (Marzbani et al., 2016; Gileles, 2018). Summarised, EEG measures and records electrical impulses quantified in patterns of four different brain waves. These EEG recordings are used in neurofeedback treatment.

Wyrwicka and Sterman (1968) were one of the first researchers who observed that brain waves not only indicate physiological and behavioural states but can also be consciously modified with learning principles of operant conditioning. Hence, with rewards or punishment following desirable or undesirable brain states, preferred brain states can be conditioned and regulated (Skinner, 1948; Wyrwicka & Sterman, 1968). In EEG neurofeedback treatment, EEG indices of interest are extracted and transferred to external devices, where brain states are converted into visual and/ or audio signals presented to the subject (Bink et al., 2016; Marzbani et al., 2016). Brain states are reflected, for example, by the speed of an animated character moving in a game environment. When the desirable brain activity is achieved, rewards, like granting credits follow (e.g. Geladé et al., 2018). EEG neurofeedback is often applied in a patient-directed approach, meaning that trained and certified therapists provide the treatment (Biofeedback certification international alliance, 2021; Vernon et al., 2004). Treatment sessions are approximately 30 to 45 minutes long, and the number of sessions varies from 20 to 40 (Vernon et al., 2004; Marzbani et al., 2016).

Next to the context, duration and frequency, EEG neurofeedback treatment is conducted by following different neurofeedback procedures, also called treatment protocols. Per protocol, other brain regions or brain waves are targeted during training. Thus, different treatment protocols aim at conditioning different brain waves. In ADHD treatment, three protocols are considered standard procedures due to a sufficient research base showing correlations between these protocols and ADHD symptom improvement, as well as neurophysiological differences to children not diagnosed with ADHD. These protocols are the Theta/Beta ratio (TBR) protocol, the sensorimotor rhythm (SMR) protocol, and the slow cortical potentials (SCP) protocol (Arns et al., 2014).

First, the Theta/Beta ratio describes the ratio between the slow brain wave theta (4 – 7 Hz) and the fast brain wave beta (13 – 30 Hz). A study by Monastra and colleagues (1999) found that among children diagnosed with ADHD, the TBR was higher compared to the control group due to excess in theta activity relative to a decrease in beta activity. Based on this early study findings and results of follow-up studies, the TBR is proposed to be a measure to differentiate healthy children from those diagnosed with ADHD (Arns et al., 2012). Thereby, decreasing the TBR is often applied in neurofeedback protocols and has also shown to be effective in reducing symptoms of ADHD (Arns et al., 2012; Arns et al., 2014; Gevensleben et al., 2010; Monastra et al., 2002). Second, the sensorimotor rhythm (SMR) relates to low beta frequency over the sensorimotor cortex. In 1976, Lubar and his colleague found that increasing the SMR is associated with improved hyperactivity and distractibility (Lubar & Shouse, 1976). These findings were replicated in multiple randomised controlled studies, which made the SMR protocol part of the standardised protocols for ADHD treatment (Kropotov et al., 2005; Steiner et al., 2014). Last, slow cortical potentials (SCP) are event-related changes in cortical electrical activity measured by EEG (Birbaumer et al., 1990). The contingent negative variation (CNV), one of these potentials, was found to be reduced in children diagnosed with ADHD (Banaschewski & Brandeis, 2007). The CNV is characterised by a "negative shift in the EEG, in anticipation of an expected event, e.g. waiting for the traffic light to turn green. The amplitude of this negative shift is a reflection of the resources allocated by the brain to prepare an adequate motor or cognitive response" (Arns et al., 2014, p. 109). Hence, the reduced CNV in children with ADHD might reflect deficits in regulating energetic resources. Training SCPs by voluntarily generating positive and negative SCPs helped children with ADHD improve attentional problems due to improved SCP regulation (Drechsler et al., 2007; Strehl et al., 2006).

The overall efficacy of EEG neurofeedback treatment for ADHD applied in a patient-directed approach has been researched for some decades (e.g. Lubar & Shouse, 1976) and has been sharply debated. Probable reasons are significant methodological limitations in early studies examining its effect (Arnold et al., 2013). Hence, little qualitatively sufficient evidence was present in the literature that assessed the effect of neurofeedback treatment for ADHD. However, to date, recently published research shows promising findings. A meta-analysis by Arns et al. (2020), including recent systematic reviews, meta-analyses, and multi-cantered randomised controlled trials (RCTs), assessed the evidence of neurofeedback treatment based on strict APA guidelines. Hence, their results relied, for example, on more than two independent RCTs, and effect sizes were taken into consideration. They found that four multicenter RCTs presented significant superiority of EEG neurofeedback treatment to semi-active control groups, with medium (Cohens' d = .54) to large (Cohens' d = .80) effect sizes (Gevensleben et al., 2010; Geladé et al., 2018; Steiner et al., 2014; Strehl et al., 2017).

Present Study

Even though EEG neurofeedback seems to be a promising alternative treatment method for ADHD, one major limitation is its reliance on trained and certified therapists. Hence, this treatment might be a non-pharmacological alternative but is not more easily accessible than other psychotherapeutic offers, often connected to long waiting times, as mentioned above. In recent years, portable neurofeedback devices have been developed (Guan Lim et al., 2020). Portable, due to their simpler technology like the incorporation of a few electrodes only, e.g. within a headband (MyndPlay, 2022). With these developments, EEG neurofeedback could be delivered in non-patient-centred contexts, e.g. at home or at school, which improves access. Guan Lim et al. (2020) already talked about a "clear shift towards delivering [EEG] intervention at home or even in school" (Guan Lim et al., 2020, p. 1). Moreover, some studies already hinted that portable neurofeedback treatment is an effective treatment option. For example, Antle et al. (2019) found significant effects of neurofeedback treatment applied at school in self-regulating anxiety. Nevertheless, to date, no outline of portable neurofeedback treatment regarding efficacy, devices used, or in general, its scope in the context of ADHD treatment is present in the literature. Hence, this review aims to conceptualise the scope of portable EEG neurofeedback treatment applied at home or school to treat children diagnosed with ADHD. The following research questions are going to be examined to do so:

1) What EEG neurofeedback devices are used in neurofeedback treatment applied at home or school for ADHD?
2) What evidence is presented in literature about EEG neurofeedback training applied at home or at school in reducing symptoms of ADHD?
3) What measurement tools did studies in the literature about EEG neurofeedback training use to monitor symptoms of ADHD?

Method

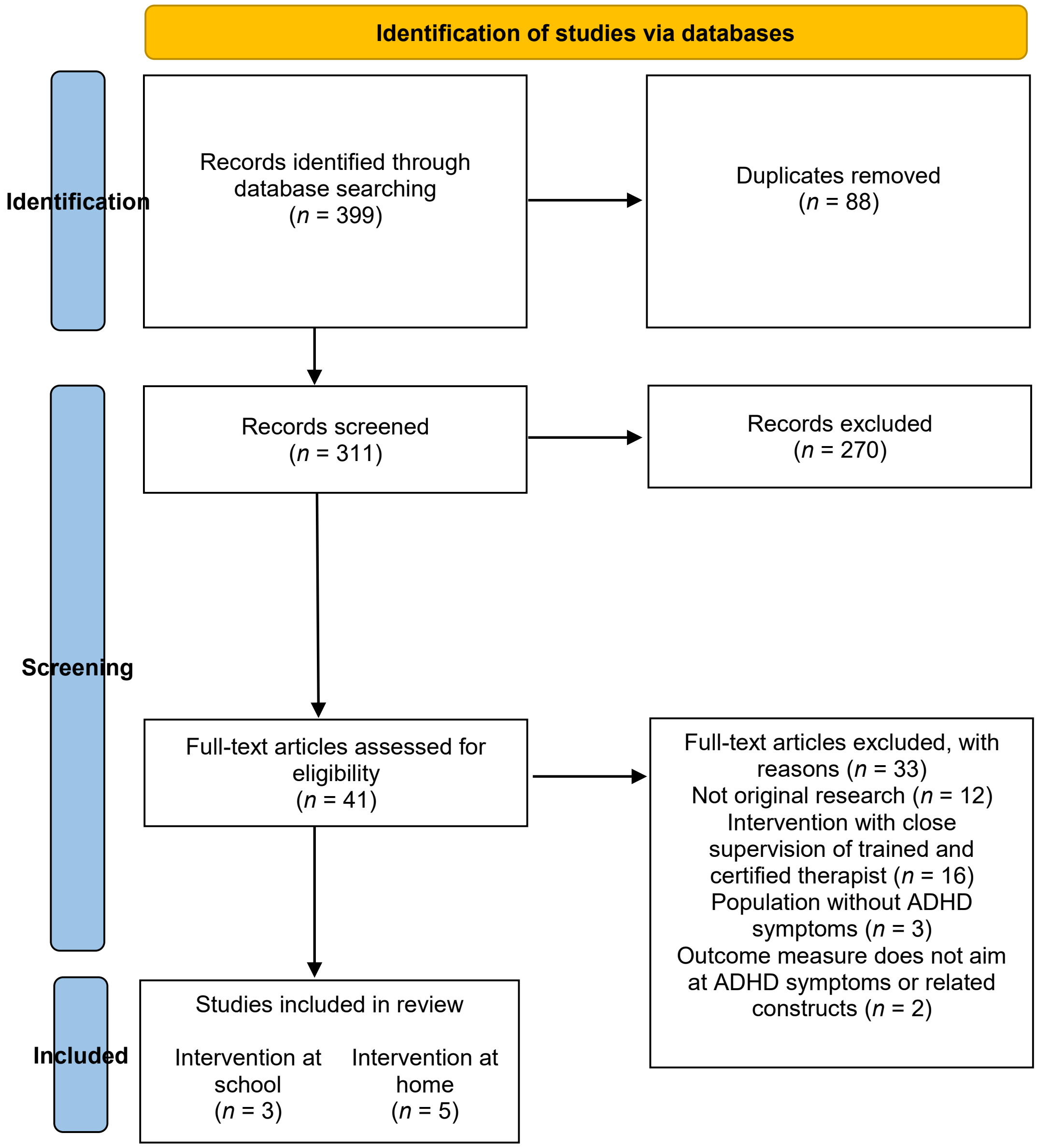
The present literature review is a systematic scoping review based on the guidelines by Peters et al. (2015). It aims to capture the current body of research on the use of EEG neurofeedback technology in home or school settings to treat symptoms of ADHD in children. This review collected data from three databases: PsycInfo, Scopus, and Web of Science. PsycInfo was a primary choice, as this database is designed explicitly for psychological and mental health research. Scopus and Web of Science were chosen to broaden the search of articles by exploring additional research fields like computer science and neuroscience. The search string used for all three databases was the following: (Neurofeedback OR "EEG biofeedback" OR neurotherapy OR biofeedback) AND ("mental health disorder" OR "mental illness" OR "mental disorder" OR "psychiatric illness" OR ADHD OR "Attention Deficit Hyperactivity Disorder*") AND (Remote OR "at home" OR ambulatory OR school).

The search was limited to articles in German or English language. Additionally, only articles from 2010 onwards were taken into consideration. Even though EEG neurofeedback in the treatment of ADHD has been researched for some decades (Arns et al., 2014), the portable use at home or in school is a relatively new approach. Hence, to exclude possible outdated neurofeedback technology and focus on new developments, articles from before 2010 were not taken into account. Additional inclusion criteria were a study sample of 18 years of age or younger diagnosed with ADHD. Also, studies had to apply portable EEG neurofeedback interventions at home or in a school setting with no close supervision of clinical psychologists to improve ADHD symptoms. Further, articles included needed to describe original research papers, and, for example, no literature reviews.

Studies were first screened on the title and then on the abstract. In doing so, 270 studies were excluded (see Figure 1). Exclusion criteria were EEG neurofeedback interventions applied in a patient-centred context, supervised by trained clinicians; the mean age of participants being above 18 years; targeted mental health symptoms not being related to ADHD; not original research studies. In the second step, the full text of the article was reviewed to be assessed for eligibility based on the inclusion criteria. Finally, eligible articles were read and analysed regarding the research questions. See Figure 1 for the study selection process according to the PRISMA guidelines (PRISMA, 2021).

Figure 1

Flow Chart of inclusion/ exclusion process of studies selected for this literature review



Results

General characteristics of included studies

Table 1 provides an overview of the study characteristics. The sample size varied between $N = 2$ and $N = 149$ ($M = 57.25$, $SD = 44.20$). Participants were children, with an age range from 6 to 11 years ($M = 9.42$, $SD = 1.02$), with the majority being clinically diagnosed with ADHD (86.8 %).

Most studies ($n = 5$) researched the effect of EEG neurofeedback treatment on ADHD, with treatment applied in a home setting. Three of the reviewed studies applied treatment in a school setting. Here, neurofeedback sessions were supervised by teachers or research assistants (Jiang et al., 2021; Minder et al., 2018; Steiner et al., 2014). Whereas in the study of Steiner et al. (2014) and Minder et al. (2018), the supervisors had a passive role in providing minimal help, if required, supervising teachers of the study by Jiang et al. (2021) were advised to provide positive feedback five times during a session. However, in all treatment modalities, participants performed the neurofeedback exercises primarily independent.

Table 1

Characteristics of included studies, study setting

Author, year	Type of sample	Type of setting; (un)supervised	*N* (Exp./Ctrl.)	Mean age; ± SD; age range
(Georgiou et al., 2019)	Diagnosed with ADHD	At home; no supervision	53	9.98 ± 1.85
(Jiang et al., 2021)	Diagnosed with ADHD	At school; supervised by teacher	2	6.10
(Johnstone et al., 2017)	Diagnosed with ADHD (*n* = 44) ; Suffer from ADHD symptoms (*n* = 41)	At home; no supervision	85 (44/41)	9.81 (7.4 - 12.8)
(Luo et al., 2022)	Diagnosed with ADHD	At home; no supervision with monitoring	57 (25/27/ 28)	8.94 (7.1 - 12.3)
(Minder et al., 2018)	Diagnosed with ADHD	At school; supervised by teacher	38 (19/19)	11.37 ± 1.7
(Purper-Ouakil et al., 2022)	Diagnosed with ADHD	At home; no supervision with monitoring	149 (90/59)	10.1 ± 1.8
(Steiner et al., 2014)	Diagnosed with ADHD	At school; supervised by RA	104 (34/34/36)	8.4 ± 1.1
(Zhang et al., 2021)	Diagnosed with ADHD	At home; no supervision	12 (4/4/4)	8.75 (7 - 10)

Note. N = Sample size; Exp./Ctrl. = Sample size of experimental group and control group(s); SD = Standard Deviation; RA = Research assistant. No supervision = Participants own responsibility to independently conduct prescribed neurofeedback sessions. With monitoring = Research teams monitored progress of participants and contacted parents if treatment plan was not met.

Devices and software used during neurofeedback training

Five different portable EEG neurofeedback devices and software were used in the reviewed studies. The device used the most (n = 4) was the NeuroSky MindWave EEG device in combination with the software Focus Pocus (see Table 2). MindWave consists of one active electrode placed on the user's forehead and an ear-clip reference ground electrode (see Figure 2) (NeuroSky, 2015). It transmits brain state information of low/ high relaxation/ attention states and an averaged Zen state to the end device for use by the software Focus Pocus (Johnstone et al., 2012). The MyndBand EEG device is comparable to MindWave, with its' one active dry electrode placed on the subject's forehead (see Figure 3). Further, similar to MindWave, attention levels are exported and transmitted to the end device for use by the corresponding software Reefocus (Kanellos et al., 2018).

Different to the other EEG devices, Purper-Ouakil et al. (2022) and Steiner et al. (2014) used ones consisting of multiple electrodes. The training device used by Purper-Ouakil et al. (2022) recorded EEG data from 8 dry scalp electrodes combined in a cap (see Figure 4). Steiner et al. (2014) used an EEG device looking like a bicycle helmet with embedded electrodes. Nevertheless, no further information of this EEG device can be drawn, as the corresponding source cited by Steiner et al. (2014) describes a neurotechnological armband dissimilar to the described helmet in the study.

Figure 2

Neurosky MindWave EEG device

Note. From "MindWave Mobile 2 – Brainwave Sensing Headset," by NeuroSky, 2015, Retrieved June 3, 2022, from https://store.neurosky.com/pages/mindwave.

Figure 3

MyndBand EEG device during Reefocus game play

Note. From "Evaluating the relation between the EEG brainwaves and attention measures, and the children's performance in REEFOCUS game designed for ADHD symptoms improvement," by Georgiou, E., Thanos, K.-G., Kanellos, T., Doulgerakis, A., & Thomopoulos, S. C. A., 2019, *Smart Biomedical and Physiological Sensor Technology XVI, 11020*, p.3 (https://doi.org/10.1117/12.2518901).

Figure 4

Mensia Koala intervention set up

Note. From "Digital therapeutics – A way to cure neuropsy disorders without drugs," by C. Gonzalez, 2018, *Inspiralia*, (https://www.inspiralia.com/digital-therapeutics/).

All corresponding softwares fed back transmitted brain states with visualisations displayed on a computer or tablet screen. In Focus Pocus, for example, the sent information of attention, relaxation or Zen levels are visualised with the speed of a wizard character's levitation (see Figure 5) (Etka, 2015; Johnstone et al., 2017). In the software used by Minder et al. (2018), participants had to steer a displayed feedback item on the screen, e.g. a fish, upward or downward by changing brain activity (see Figure 6).

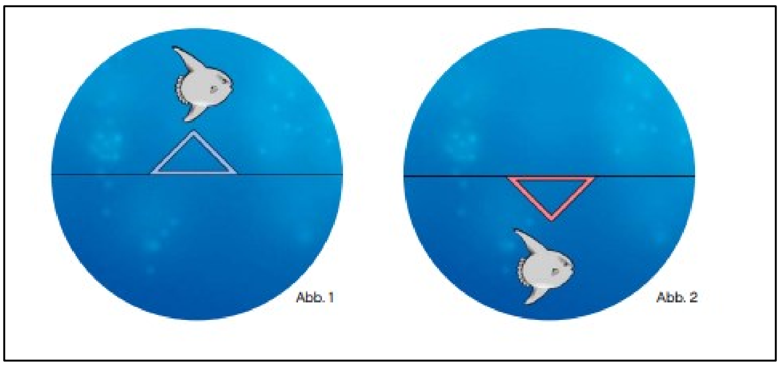
Figure 5

Focus Pocus game environment

Note. From "All you need to know about Focus Pocus," by Etka, E., 2015, ADHD Video Game - Focus Pocus by NeuroCog - Neurofeedback Webinar. Retrieved June 3, 2022, from https://www.slideshare.net/neurocog/all-you-need-to-know-about-focus-pocus?from_action=save.

Figure 6

Theraprax game environment



Note. From "THERA PRAX® MOBILE – Bio - und Neurofeedback-System," by Neurocare group AG, 2022 (https://www.neurocaregroup.com/de/thera-prax-mobile_de).

No overall commonalities or differences between EEG devices and softwares can be found regarding the setting. The Neurosky MindWave device, in combination with Focus Pocus, is used at home and school, among reviewed articles. Further, no differentiation between the complexity of EEG devices in relation to the setting can be made, as both more complex EEG devices are used in a school and home setting, respectively (Purper-Oakil et al., 2022; Steiner et al., 2014). Except for the NeuroSky MindWave EEG device, all devices in the reviewed studies export EEG data of standardised neurofeedback protocols of ADHD, namely SCP, SMR and TBR protocols. MindWave exports EEG data of alpha and beta frequency bands.

Table 2

EEG Softwares and devices used in studies

Author, year, setting	Software	Applied modules of software	Hardware/ protocol	Outcomes
(Georgiou et al., 2019) At home	Reefocus	CT (WM, IC, DA, SA, SeA, MC)	MyndPlay headset/ TBR	Attention, TBR
(Jiang et al., 2021) At school	Focus Pocus	CT (WM, IC) and NFT (atten., relax., zen) combined	Neurosky MindWave/ alpha/ beta band	Observations of on-task behaviour, Observations of off-task behaviour
(Johnstone et al., 2017) At home	Focus Pocus	CT (WM, IC) and NFT (atten., relax., zen) combined	Neurosky MindWave/ alpha/ beta band	Inattention, hyperactivity, aggression, externalising
(Luo et al., 2022) At home	Focus Pocus	CT (WM, IC); NFT (atten., relax., zen); CT (WM, IC) and NFT (atten., relax., zen) combined	Neurosky MindWave/ alpha/ beta band	Inattention, hyperactivity, IC, WM, functional impairment
(Minder et al., 2018) At school	NeuroConn training software	SCP regulation	THERA PRAX/ SCP	Inattention, hyperactivity, executive functions, IC, WM, engagement, off-task behaviour

(Purper-Ouakil et al., 2022) At home	Mensia Koala	TBR down-training; SMR up-training	Mensia Koala EEG cap/ SMR or TBR	Inattention, hyperactivity, IC, WM
(Steiner et al., 2014) At school	Not named	TBR down-training; CT (atten., WM)	Not named (like helmet)/ TBR	Inattention, hyperactivity, executive functions, IC, WM
(Zhang et al., 2021) At home	Focus Pocus	CT (WM, IC); NFT (atten., relax., zen); CT (WM, IC) and NFT (atten., relax., zen) combined	Neurosky MindWave/ alpha/ beta band	Inattention, hyperactivity, IC, WM

Note. CT = Cognitive training; WM = Working memory; IC = Inhibitory control; DA = Delay aversion; SA = Sustained attention; SeA = Selective attention; MC = Motor coordination; NFT = Neurofeedback training; atten. = Attention; relax. = Relaxation; SCP = Slow cortical potentials; TBR = Theta/ Beta ratio; SMR = Sensorimotor rhythm.

Evidence of portable EEG neurofeedback to treat ADHD

Five out of eight studies are RCT studies, with four of them using active controls (Luo et al., 2022; Minder et al., 2018; Purper-Ouakil et al., 2022; Steiner et al., 2014). Steiner et al. (2014) present significant reductions in parent-rated inattention symptoms of ADHD, with a large effect size (Cohen’s d = .80). Purper-Ouakil et al. (2022), the only study with a medication active control group, present significant decreases of researchers rated ADHD symptoms, with a large effect size (Hedge’s g =1.05). Luo et al. (2022) and Minder et al. (2018) both present significant reductions in parent-rated inattention, hyperactivity and inhibition symptoms of participants, with large effect sizes (see Table 3). Here, values of Eta square (η2) and Partial Eta square (ηp2) of 01, .06, and .14 represent small, medium and large effects, respectively (Cohen 1991). Overall most studies present weak to moderate or missing effect sizes (see Table 3).

Further, this study shows that EEG neurofeedback treatment at school presents higher effect sizes compared to treatment at home (Jiang et al., 2021; Minder et al., 2018; Steiner et al., 2014). Steiner et al. (2014) found significant improvements in parent-rated attention levels of participants, with a high effect size (Cohen’s d = .80). Also, Jiang et al. (2021) present significant increases in on-task behaviour in a self-study setting, rated by research assistants with a high effect size (ϕ = .79; ϕ = .67).

Table 3

Study design, outcomes of studies

Author, year	Study design	Control condition	Frequency of intervention	Outcomes Of pre-post time points/ within reversal design	Significant improvements	Reported effect size
(Georgiou et al., 2019)	Pilot study	Missing	4 weeks	Attention level	($p < .05$)	Missing
				TBR	($p < .05$)	
(Jiang et al., 2021)	Reversal single case design With a reversal phase and a follow-up phase	Missing	25 sessions of 15 to 20 min; 9 weeks	Self-study setting:		
				ONT-EX	Missing	A ϕ = .79; B ϕ = .67
				ONT-SBM	Missing	A ϕ = .10; B ϕ = .02
				OFF-MA	Missing	A ϕ = .68; B ϕ = .34
				OFF-PB	Missing	A ϕ = .79; B ϕ = .67
				Small class setting:		
				ONT-EX	Missing	A ϕ = .30; B ϕ = .66
				ONT-SBM	Missing	A ϕ = .20; B ϕ = .18
				OFF-MA	Missing	A ϕ = .40; B ϕ = .44
				OFF-PB	Missing	A ϕ = .30; B ϕ = .78
(Johnstone et al., 2017)	Randomised waitlist control trial Pre-post assessment	Waiting list	25 sessions of 20 min; 8 weeks	Inat.	($p < .05$)	$\eta_p^2 = .07$
				Hyper.	($p < .05$)	$\eta_p^2 = .11$
				EF.	($p < .05$)	$\eta_p^2 = .14$
				AttenP.	($p < .05$)	$\eta_p^2 = .07$
				Ag.	($p < .05$)	$\eta_p^2 = .07$
				Ext.	($p < .05$)	$\eta_p^2 = .12$
				ADHD symptoms (parents)	($p < .05$)	$\eta_p^2 = .20$

				ADHD symptoms teacher)	$(p < .05)$	$\eta_p^2 = .34$
				ADHD symptoms (sig. other)	*ns*	-
(Luo et al., 2022)	Randomised active control design Pre-post assessment	Active control: CCT; COM	34 sessions of 15 min; 12 weeks	Inat.	$(p < .05)$	$\eta^2 = .17$
				Hyper.	$(p < .05)$	$\eta^2 = .27$
				Inhib.	$(p < .05)$	$\eta^2 = .15$
				WM	$(p < .05)$	$\eta^2 = .15$
				life skills	$(p < .05)$	$\eta^2 = .07$
				school domain	*ns*	-
(Minder et al., 2018)	Randomised active control design Pre-post assessment	Active control: CogT school/clinic; NF school/clinic	28 sessions of 45 min; 12 weeks	Inat. (parents)	$(p < .05)$	$\eta_p^2 = .32$
				Hyper. (parents)	$(p < .05)$	$\eta_p^2 = .24$
				Inat. (teachers)	$(p < .05)$	$\eta_p^2 = .08$
				Hyper. (teachers)	*ns*	-
				IC. (parents)	$(p < .05)$	$\eta_p^2 = .34$
				WM (parents)	$(p < .05)$	$\eta_p^2 = .32$
				IC. (teachers)	$(p < .05)$	$\eta_p^2 = .15$
				WM (teachers)	$(p < .05)$	$\eta_p^2 = .14$
				Engagement	$(p < .05)$	$\eta_p^2 = .19$
				Off task behaviour	$(p < .05)$	$\eta_p^2 = .08$
(Purper-Ouakil et al., 2022)	Randomised control design Pre-post assessment	Active control: Methylphenidate	36 sessions of 20 min; 9 weeks	ADHD total (researchers)	$(p < .05)$	Hedges' g = - 1.05
				Inat. (researchers)	$(p < .05)$	Missing
				Hyper. (researchers)	$(p < .05)$	Missing
				ADHD total (parents)	$(p < .05)$	Missing

				Inat. (parents)	($p < .05$)	Missing
				Hyper. (parents)	($p < .05$)	Missing
				ADHD total (teacher)	*ns*	Hedges' g = - .20
				Inat. (teachers)	*ns*	-
				Hyper. (teachers)	*ns*	-
				IC, WM	($p < .05$)	Missing
				Inat. (parents)	($p < .05$)	Cohen's *d* = - .80
(Steiner et al., 2014)	Randomised control design Pre-post assessment	Active control: Cognitive training; Computer attention training	40 sessions of 45 min; 20 weeks	EF (parents)	($p < .05$)	Cohen's *d* = - .49
				IC (parents)	($p < .05$)	Cohen's *d* = - .32
				WM (parents)	($p < .05$)	Cohen's *d* = - .44
				Atten. (teachers)	*ns*	-
				Inat. (teachers)	*ns*	-
				Off task	($p < .05$)	Cohen's *d* = - .60
				Total eng.	*ns*	-
				WM (participants)	($p < .05$)	Missing
				IC (participants)	*ns*	Missing
(Zhang et al., 2021)	Multiple baseline single-case experimental design	Each participant serving as own active control during baseline phase	20 sessions of 25 min; 7 weeks	WM (parents)	*ns*	Missing
				IC (parents)	*ns*	Missing
				Inatten. (parents)	*ns*	Missing
				Hyper. (parents)	*ns*	Missing

Note. TBR = Theta/ Beta ratio; ONT-EX = On-task behaviour without inappropriate body movements; ONT-SBM = On-task behaviour with spontaneous body movement; OFF-MA = Off-task motor activity; OFF-PB = Off-task passive behaviour; ϕ = Phi effect size; ηp2 = partial eta-squared effect size; Inat. = Inattention; Hyper. = Hyperactivity; EF = Executive Functions. AttenP. = Attention problems; Ag. = Aggression;

Ext.= Externalizing; Ns = Not significant; CCT = computerized cognitive training; COM = neurofeedback and computerized cognitive training combined; CogT = Computerized cognitive training; IC = Inhibitory control; WM = working memory; Total eng. = Total engagement.

Outcomes of interventions and measurement tools

Different measurement tools are used within studies to monitor symptoms of ADHD. Most studies used questionnaires that needed to be filled out by teachers, parents and/ or research assistants (see Table 4). Questionnaires used the most were the ADHD rating scale (ADHD- RS) (n = 4), the Conners 3 scale (n = 3), and the Behaviour Rating Inventory of Executive Function (BRIEF) (n = 5) (see Table 3).

The ADHD-RS assesses the severity of ADHD symptoms. It includes both symptom dimensions of ADHD based on the DSM-5, namely inattention and hyperactivity/ impulsivity. The ADHD- RS has high internal validity (α = .86), and good test-retest reliability (r = .82) (Faries et al., 2001). The Conners 3 scale was used to screen characteristic ADHD behaviour. There are different forms of the scale to be applied by teachers and parents. This scale also serves high internal validity (α = .89), and test-retest reliability (r = .86) (Conners, 2015). The BRIEF assesses executive functions. It includes eight factors of executive functioning. The four studies that used this questionnaire focused on inhibition and working memory. Its test-retest reliability (r = .80) and internal validity (α = .80) are high (Gioia et al., 2000). Solely the study of Georgiou et al. (2019) used the EEG devices' internal data to measure attention level changes. Therefore, it is the only study considering direct participant measures and not third-party assessments.

Table 4

Measurement tools of outcomes, time point of measurement

Study	Outcome	Measurement tool	Filled out by whom?/ conducted by	Time points
(Georgiou et al., 2019)	Attention level TBR	EEG device	-	First and last quartile of gaming sessions
(Jiang et al., 2021)	ONT-EX in self-study & small class setting	Observation	Two research assistants	First baseline (2-weeks) First intervention (2-weeks) Second baseline (2-weeks) Second intervention (7 weeks) Follow up (2-weeks)
	ONT-SBM in self-study & small class setting	Observation	Two research assistants	
	OFF-MA in self-study & small class setting	Observation	Two research assistants	
	Off-PB in self-study & small class setting	Observation	Two research assistants	
(Johnstone et al., 2017)	Inattention, hyperactivity/ impulsivity	ADHD-RS	Parents; classroom teachers; significant others	Pre-training and post-training (8 weeks after pre-training assessment)
	Inattention, hyperactivity, executive functions	Conners 3-P	Parents	
	Attention problems, aggression, externalising	CBCL	Parents	
(Luo et al., 2022)	Inattention, hyperactivity/ impulsivity	ADHD-RS	Parents	Pre-training session, post-training session (3 months after pre-training assessment)
	Inhibitory control, working memory	BRIEF	Parents	
	Daily functional impairment (life skills school and learning)	WFIRS-P	Parents	
(Minder et al., 2018)	Inattention, hyperactivity, executive eunctions	Conners 3-P	Parents, teachers	Baseline; pre-training;

	Inhibitory control, working memory	BRIEF	Parents, teachers	post-training (3 months after pre-training assessment)
	Engagement, off-task behaviour	BOSS	Two blinded trained observers	pre-training; post-training (3 months after pre-training assessment)
(Purper-Ouakil et al., 2022)	Inattention, hyperactivity/ impulsivity	ADHD-RS	Researchers, Parents, Teachers	Baseline (D0); intermediate training (D60); post-training (D90)
	Inhibitory control, working memory	BRIEF	Researchers	Baseline (D0); post-training (D90)
(Steiner et al., 2014)	Inattention, executive functioning	Conners 3-P	Parents	
	Inhibitory control, working memory	BRIEF	Parents	
	Inattention	Conners 3-T	Teachers	Pre-training; post-training
	Attention	SKAMP	Teachers	
	Engagement, off-task behaviour	BOSS	Two research assistants	
(Zhang et al., 2021)	Working memory	2-back task	Computerised task by participant	
	Inhibitory control	SSRT	Computerised task by participant	
	Inhibitory control, working memory	BRIEF	Parents	Pre-training, intermediate training, post-training
	Inattention, hyperactivity/ impulsivity	ADHD-RS	Parents	

Note. TBR = Theta-to-Beta ratio; ONT-EX = On-task behaviour without inappropriate body movements; ONT-SBM = On-task behaviour with spontaneous body movement; OFF-MA = Off-task motor activity; OFF-PB = Off-task passive behaviour; ADHD-RS = ADHD rating scale;

CBCL = Child Behaviour Checklist; BRIEF = Behaviour Rating Inventory of Executive Function; WFIRS-P = the Weiss Functional Impairment Scale- Parent Report; BOSS = Behavioural Observation of Students in Schools; SSRT = Stop-signal reaction time task

Discussion

Main findings

This scoping review summarised the current body of research on the use of portable EEG neurofeedback treatment of ADHD at home or in school within the last 12 years to become aware of the current research status. In general, the findings show that little research on this topic has been conducted, with only eight studies present in this review. Further, most studies present weak to moderate effect sizes. Interventions conducted at school show higher effects on ADHD symptomatology than at-home treatment.

One reason for portable EEG neurofeedback interventions' moderate to weak overall effects on ADHD symptoms might be its unimodal, standardised treatment approach. ADHD is a complex disorder with a high degree of heterogeneity in terms of symptoms, comorbidities and the course and response to therapy (AWMF, 2017; Loo et al., 2018). For example, symptoms of ADHD show developmental changes, with different symptom dimensions present in different forms at different ages. Whereas for primary school-aged children diagnosed with ADHD symptoms like motoric agitation and hyperactivity are often in the foreground, for adolescence, hyperactivity often manifests itself in inner restlessness (Rhode et al. 2019). Additionally, ADHD is commonly associated with other psychiatric disorders. Up to 85% of children and adolescents diagnosed with ADHD are diagnosed with an additional comorbid condition, in 50 % of the cases from disruptive mood dysregulation disorder (Döpfner et al., 2013; Pliszka, 1998). Therefore, due to the complexity of ADHD, national treatment guidelines recommend individualised multimodal treatment for children diagnosed with ADHD, dependent on symptom severity and age (Coghill et al., 2021; AWMF, 2017). With ADHD being a complex and heterogeneous disease, it might be unexpected that a standardised, unimodal neurofeedback intervention is equally effective for all children and adolescents diagnosed with ADHD.

Another finding of this study is that overall, studies implementing neurofeedback treatment at school present larger effect sizes of improved symptoms of ADHD compared to treatments applied at home. This difference also applies to studies using the same EEG device and comparable study designs (Jaing et al., 2021; Zhang et al., 2021). One explanation might be the presence of supervisors during treatment sessions at school and their absence during at-home treatment. Based on the self-determination theory, motivation and task commitment are associated with intrinsic and extrinsic motivation (Gagne & Deci, 2005). Extrinsic motivation relates to performance on an activity for instrumental reasons like external rewards. Supervision is another extrinsic motivating factor (Ratliff & Hicks, 1998).

Hence, the presence of supervisors during treatment sessions at school might have led to higher extrinsic motivation and commitment of participants during sessions. Thereby, supervisors being present might have served as a confounding variable explaining the larger effect sizes.

Strength and limitations

One strength of this study is the overview it provides in terms of the present evidence in current literature regarding the use of portable EEG neurofeedback training as a treatment method for ADHD. To date, no literature review is present on this topic, hence, this review provides a first insight into the limits and opportunities of portable EEG neurofeedback in ADHD treatment. Still, this study has some limitations. First, the number of studies in this literature review is low, with only eight studies to be reviewed. Hence, little research has been conducted about the effectiveness of treatment with the use of portable EEG technology on ADHD. Probable reasons might be the still innovative application of portable EEG technology for use in a clinical context, as most portable EEG neurofeedback devices are advertised as consumer-grade products (MyndPlay, 2022). A second limitation is the methodological quality of reviewed studies. Of the four RCT studies, none is double-blind. Further, all four studies deviate from calculated power analyses effect sizes, with the sample of the study of Purper-Ouakil et al. (2022) and Steiner et al. (2014) deviating the smallest.

Third, the reviewed studies' assessment and monitoring of ADHD symptoms are limited. Most studies solely used third-party assessments of teachers and parents to monitor symptoms. Nevertheless, when assessing symptoms of ADHD, it should be aimed at a comprehensive assessment, including the participant's own perspectives (Rhode et al., 2019). Parent and teacher ratings have been considered valid treatment endpoints to rate the clinical efficacy of non-pharmacological treatment approaches (Sonuga-Barke et al., 2013). Still, the reliability of teacher ratings has been questioned (Arns et al., 2020; Minder et al., 2018). A recent meta-analysis by the European ADHD Guidelines Group (EAGG) found that teachers were more sensitive in rating ADHD treatments with a fast onset of effect, like pharmacological treatments, compared to those that exert their effects more slowly, like behavioural interventions (Cortese et al., 2018). Also, research found low concordance between parent and teacher ratings and between self-reports and third-party reports on ADHD symptomatology (Faraone et al., 2015; Rohde et al., 2019). However, no suggestions or guidelines have been provided by the DSM on combining data from different information sources, other than that assessments should be as comprehensive as possible. Discrepancies between different sources of raters are commonplace (American Psychiatric Association, 2013). Reasons are, for example, that children behave differently in different settings in which they are confronted with different impairments (Rohde et al., 2019).

Future research recommendations

With only eight studies present in this review, it is shown that evidence-based research in this field is still rare. Thereby, more research is needed. Hence, future studies should further investigate the effect of portable EEG neurofeedback treatment on ADHD symptoms. Hereby, the focus should be on testing portable EEG neurofeedback interventions at the individual level, e.g., using multiple baseline single-case experimental designs. As mentioned above, ADHD is heterogenous in its symptoms and also in its brain activity (Loo et al., 2018). Therefore, individualised treatment is needed. With the use of single-case experimental designs, a scientific basis to tailor interventions to individuals could be provided.

Also, future studies should implement device internal ADHD symptom assessments to control for expectancy bias of third-party assessors and aim at a comprehensive assessment. Using EEG neurofeedback devices for treatment allows for tracking objective, device internal measurements, e.g. attention level changes over time. Still, Georgiou et al. (2019) is the only study using device internal data to assess treatment efficacy. Hence, future studies should include device internal data as an additional assessment option to aim for a comprehensive assessment of treatment effects. This also encompasses self-assessment data of participants. As mentioned above, in none of the studies present in this literature review, participants' perspectives were taken into account, even though it is essential in the assessment process (Rohde et al., 2019). Hence, future studies should include self-assessment questionnaires for participants, for example, by adding them to the software's game environment.

Further, future studies should include follow-up measures of treatment effects. Stimulant medication is most widely used in treating ADHD (National Institute for Health and Care Excellence, 2018; Michelson et al., 2002). One drawback of this treatment is its limited long-term effect (Wang et al., 2013). A recent meta-analysis reported promising findings of a sustained impact of EEG neurofeedback treatment. Van Doren et al. (2018) researched the effect of EEG neurofeedback applied in clinical settings. They found significant treatment efficacy for teacher and parent-rated symptoms with sustained effects after six to twelve months. Nevertheless, less is known about whether this effect holds for neurofeedback applied with portable devices at home and school, as none of the reviewed studies included follow-up measures. Gaining such insight would be of value, as

Conclusion

This study shows that the evidence of effective use of portable EEG neurofeedback in the treatment of ADHD is scarce and seems to present less promising findings regarding its effectiveness due to overall weak to moderate effect sizes. Still, scattered reported significant reductions in ADHD symptoms after portable EEG neurofeedback treatment hint to some neurofeedback protocols being effective. Hence, no generalised interference about the effectiveness of this treatment method can be drawn. One reason is the heterogeneity of devices used, neurofeedback protocols used, and the setting in which treatment was applied in studies present in this review. Another reason is the probable need for individualised neurofeedback protocols for patients diagnosed with ADHD due to this disease's complex and heterogenous symptomatology. Therefore, future research on this topic is indispensable and valuable. With gaining additional insights into the effect and functionality of portable EEG neurofeedback treatment, an additional, readily accessible, non-pharmacological treatment option could be added to the treatment repertoire of ADHD.

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